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Geophysical investigations of subglacial lakes Vostok and Concordia, East Antarctica

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Geophysical investigations of subglacial lakes Vostok and Concordia, East Antarctica

by

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Geophysical investigations of subglacial lakes Vostok and Concordia, East Antarctica

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The subjects for this study are two subglacial lakes – Vostok and Concordia – located in East Antarctica. Lake Vostok is the largest known subglacial lake on Earth. Melting and freezing at the ice-water contact are known to occur in both lakes. These internal processes are important subjects for numerical modeling. The precise knowledge of the lake's bathymetry and the distribution of unconsolidated sediments at the bottom of the lake are required boundary conditions for such modeling. The ultimate goal of this research was to develop 3D bathymetry models and to establish the distribution of unconsolidated sediments for both lakes.

Joint interpretation of airborne gravity and seismic data was performed for Lake Vostok, revealing that the lake is hosted by consolidated sedimentary rocks. The modeling shows that Lake Vostok consists of two sub-basins: a larger, deeper one with water thickness exceeding 1000 m in the south and a shallower one with a water thickness of about 250 m in the north. The resulting 3D model has a substantially better correlation with seismic data than two previous models.

Lake Concordia appears to be significantly shallower with water thicknesses not exceeding 200 m for all possible host rock densities. Since the lake is relatively shallow, the sediment layer cannot be resolved. A similar pattern of freezing and melting was observed in Lake Concordia and Lake Vostok: the deeper part of the lake lies under thinner ice and is dominated by the freezing of water at the ice bottom, while in the shallower part of the lake the overlying thicker ice melts.

The analysis of seismic data in four different locations over Lake Vostok revealed the presence of unconsolidated sediments at the bottom of the lake. The sedimentary layer appears to be thicker (up to 400 m) in the northern basin, while its thickness does not exceed 300 m in the southern one.

Four different sedimentation mechanisms were considered to explain how such a thick sedimentary layer was deposited in Lake Vostok under glacial conditions. The estimates show that none of the mechanisms considered is capable of depositing the observed sedimentary layer, revealing the pre-glacial origin of Lake Vostok.

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Chapter 1: Introduction and the overview of the Dissertation

The objects for my research are two subglacial lakes in Antarctica - Lake Vostok and Lake Concordia. Both of them are situated under the approximately 4 km thick East Antarctic ice sheet. The largest subglacial lake in Antarctica - Lake Vostok - is about 300 km long and 60 km wide with the surface area of 17 000 km^2. It is located beneath the Russian Station Vostok in the middle of East Antarctica (Figure 1.1).

Currently, more than 145 subglacial lakes are known to be present in Antarctica (Siegert et al., 2005; Bell et al., 2006 and 2007), but all of them are significantly smaller than Lake Vostok. One of the largest of those, Lake Concordia, is located in East Antarctica at the distance of ~100 km to the north of Dome C (Figure 1.1). This lake is about 50 km long and 20 km wide. Lake Concordia was discovered during the airborne geophysical survey performed by the University of Texas Institute for Geophysics (UTIG) during the 1999 – 2000 survey over Dome C of the East Antarctic ice sheet. A major portion of my Dissertation is focused on Lake Vostok, although I will also analyze Lake Concordia.

Lake Concordia with an area of approximately 600-800 km^2, is the second largest subglacial lake in Antarctica over which substantial geophysical data has been collected. Recently, six other large subglacial lakes have been identified using satellite observations. These are 90˚E Lake with the area of around 2000 km^2 and Sovetskaya Lake at about 1600 km^2 (Bell et al., 2006; Figure 1.1) as well as four more large subglacial lakes (denoted A, B, C, and D) each with a surface area exceeding 1500 km^2 found at the onset of the Recovery Glacier ice stream in East Antarctica (Bell et al., 2007; Figure 1.1). These newly identified lakes have not yet been geophysically surveyed.

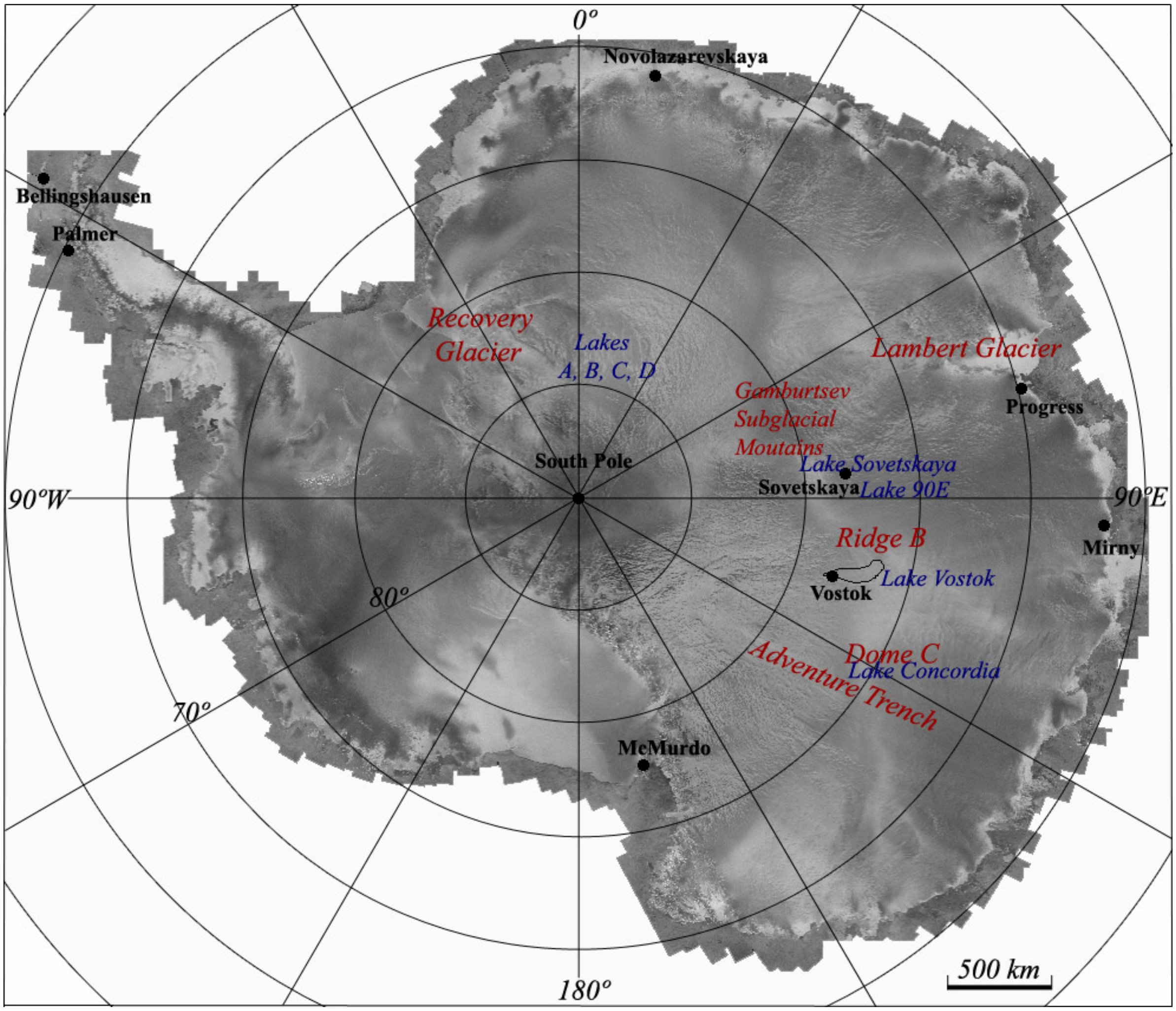


Figure 1.1 The location of the largest known subglacial lakes in Antarctica. The geographical names mentioned in the text are given in red. The black dots show the locations of the research stations. The background RADARSAT satellite image is from http://earthobservatory.nasa.gov/

By analysis of the internal layers in the ice sheet covering Lake Vostok, it was found that there is freezing (accretion) of the water on the bottom of the ice in the southern part of the lake along with melting of the ice-sheet in its northern part (Siegert et al, 2000). Those processes are believed to be coupled to water circulation within this lake (Siegert et al., 2000 and 2001, Thoma et al., 2007).

It is known that similar processes of melting and freezing at the ice-water boundary operate in Lake Concordia (Tikku et al., 2005). Since this lake is significantly less explored than Lake Vostok, the estimates of the water thickness in the lake can provide important information about it. This also allows us to compare and contrast Lake Concordia with Lake Vostok in terms of the water depth and distribution of internal processes, such as melting and freezing.

All of the internal processes within subglacial lakes are subject to numerical modeling as in Wuest and Carmac (2000) and Thoma et al. (2007). The boundary conditions for such modeling include geometry of the ice-water interface and the lake's coast line from radar sounding. The precise distribution of water in the lake, as well as the presence and distribution of unconsolidated sediments at the bottom of Lake Vostok also are very important boundary conditions required for numerical modeling of the internal processes within the lake.

In my Dissertation, I address the issues of the bathymetry of two subglacial lakes Vostok and Concordia, along with the presence and distribution of the unconsolidated sediments at the bottom of the Lake Vostok.

Chapter 2 of this Dissertation gives the overview of the existing knowledge about subglacial Lake Vostok. This chapter describes the discovery of the lake, the data from the ice core drilled at Vostok Station as well as the geological hypotheses about the origin of Lake Vostok. It also describes the available geophysical datasets, which are used in this research.

There are more than 100 seismic soundings acquired by the Russian Antarctic Expedition (RAE) in collaboration with the Polar Marine Geological Research Expedition (PMGRE) over Lake Vostok. These are mostly located in the southern portion of the lake. Another available dataset consists of the airborne geophysical data collected by UTIG during 1999/2000 field season. The last two chapters of this Dissertation are the result of the collaborative research project between UTIG, RAE and PMGRE. This aims to combine the existing datasets and to perform the joint interpretation of seismic soundings and airborne geophysical data for Lake Vostok.

Chapter 3 of my Dissertation is focused on prior 2D and 3D modeling of the UTIG airborne gravity data over Lake Vostok. One of the goals of this modeling was to find the density value for the rocks beneath the lake ("host rocks") that gave the best agreement between the gravity derived water thickness and the results of seismic measurements based on 2D inversions over several profiles. This density value was ultimately used to develop the 3D bathymetry model and sediment distribution of Lake Vostok. The ultimate results of the first part of my Dissertation, described in Chapter 3, are the following:

(1) Lake Vostok is hosted by consolidated sedimentary rocks of density 2550 kg/m^3. This density gave the best agreement between water thickness derived from gravity inversion and seismic soundings.

(2) Lake Vostok consists of two sub-basins. The larger and deeper one is located in the southern part of the lake, with the deepest part having a water thickness of more than 1000 m. The shallower basin is in the north of the lake, and it is several hundred meters deep. These basins are separated by a rise in the lake's bottom topography that is

approximately 40 km wide. Since the spacing between seismic soundings in this portion of the lake is 40 km, this feature was overlooked.

Chapter 4 describes similar research performed for Lake Concordia. Since there is no seismic constraint for Lake Concordia, the water thickness was estimated for the range of different host rock densities. Lake Concordia appears to be shallow, with the water thickness not exceeding 200 m for all possible density values of the host rocks. The water thickness in the lake becomes negative if igneous rocks of density 3000 kg/m^3 or higher are assumed to host the lake. Since the lake is relatively shallow, a sedimentary layer can not be resolved.

Comparison of the data over subglacial lakes Vostok and Concordia revealed similarities between these lakes, such as: (1) the deeper part of each lake is overlain by thinner ice and is dominated by freezing of the lake's water at the bottom of the ice sheet, and (2) the ice melting coincides with the shallower parts of both lakes, covered with thicker ice.

The results of the 2D modeling for lakes Vostok and Concordia, described in Chapters 3 and 4 respectively, were presented in September 2003 at the IX International Symposium on the Antarctic Earth Sciences (ISAES), Potsdam, Germany, as well as at the AGU Fall meeting in 2003 (Filina et al., 2003). The peer-reviewed contribution to the ISAES Conference Proceeding volume was published in 2006 (Filina et al., 2006a). The results of the 3D inversions were presented at the First Scientific Committee on Antarctic Research (SCAR) Open Science Conference in Bremen, Germany, in July 2004 (Filina et al., 2004).

Chapter 5 of my Dissertation addresses the issue of the presence of unconsolidated sediments at the bottom of Lake Vostok based on the analysis of the reflection seismic data, provided by RAE and PMGRE, in several different locations over the lake. The recorded seismograms show at least two relatively closely spaced reflections after the ice-water echo. In early publications (up to 2002) those events were interpreted as boundaries of a several hundred meters thick layer of unconsolidated sediment overlying the lake basin. However, more recent interpretations (since 2003) postulate that the secondary bottom reflections on seismic records are just side echoes due to the lake's bottom roughness.

Several hypotheses for the origin of those reflections were tested by performing seismic travel time inversion. The modeling shows that some of the reflections, but not all of them, are consistent with the hypothesis about the non-flat lake bottom. The modeling reveals the presence of a 100 – 380 m thick layer of unconsolidated sediments at the bottom of Lake Vostok. The sedimentary layer appears to be thicker in the northern part of the lake. The results of this research were presented at the 2nd SCAR Open Science Conference in Hobart, Tasmania in July 2006 (Filina et al., 2006b), as well as in August 2007 at the X ISAES, Santa Barbara, CA. The paper was published in a volume jointly sponsored by the USGS and the National Academy of Science (Filina et al., 2007a).

Chapter 6 of the Dissertation describes a revised water and unconsolidated sediment distribution for Lake Vostok. This updated 3D model incorporates the results of the previous research (described in Chapters 3 and 5), tying together all the conclusions from these research. The results were presented in August 2007 at the X ISAES, Santa Barbara, CA, where they are published as an extended abstract in on-line Proceeding Volume (Filina et al., 2007b) and are submitted to Earth and Planetary Science Letters (Filina et al., 2007c). The ultimate results are the 3D models of water and the sediment thicknesses for Lake Vostok. The good correlation of these models with seismic data

(125 m RMS of difference between gravity derived water thickness and seismic measurements in 60 points) proves several major facts about Lake Vostok:

(1) The lake is hosted by sedimentary rocks. This was confirmed by the analyses of the inclusions in the ice samples from the borehole drilled at Vostok Station and reported by Leitchenkov et al., 2007.

(2) 3D modeling of gravity data confirms the presence of a layer of unconsolidated sediments up to 400 m thick at the bottom of the lake, previously inferred from seismic data.

Different sedimentation mechanisms were considered for the 400 m of sediments at the bottom of Lake Vostok. The estimated sedimentation rate for four possible glacial mechanisms shows that they are not capable of depositing such a thick layer of unconsolidated sediments under glacial conditions, suggesting that the lake existed before glaciation.

All major conclusions from the different parts of my Dissertation are reviewed in the last section.

Chapter 2: Present state of knowledge about subglacial Lake Vostok

Among more than 145 subglacial lakes found beneath the Antarctic Ice Sheet (Siegert et al., 2005; Bell et al., 2006 and 2007) the largest one is located beneath the Russian station Vostok in East Antarctica (Figure 1.1). Lake Vostok, covered by 4 km of ice, is about 300 km long and 60 km wide. The existence of this lake was first proposed from airborne radar sounding data (Oswald and Robin, 1973) and later confirmed by satellite altimetry (Ridley et al., 1993) and seismic sounding (Kapitsa et al., 1996). Over more than a decade of the intense exploration of Lake Vostok, a lot of information about this lake was collected and analyzed. Many geophysical, glaciological, geodetic, biological and other studies were performed to unearth the origin of the lake, its present state and dynamics. Other subglacial lakes are significantly less studied, and most of the information about subglacial lakes has been derived from the studies of Lake Vostok. This chapter reviews the present state of knowledge about Lake Vostok.

2.1 The discovery of Lake Vostok

The first observation of a relatively large flat area in the vicinity of the Russian station Vostok in the middle of East Antarctica was described by the Russian pilot R. Robinson, who was performing flights connecting the Mirniy Station at the coast of Antarctica with Vostok Station located more than 1000 km inland during the 4th Soviet Antarctic Expedition. Robinson wrote a short note describing the large area of the ice near Vostok station that differs drastically from the surrounding areas by being anomalously flat (Zotikov, 2000 and references therein; see satellite image of the area in Figure 2.1). There were several similar areas in the middle part of Antarctica. They can

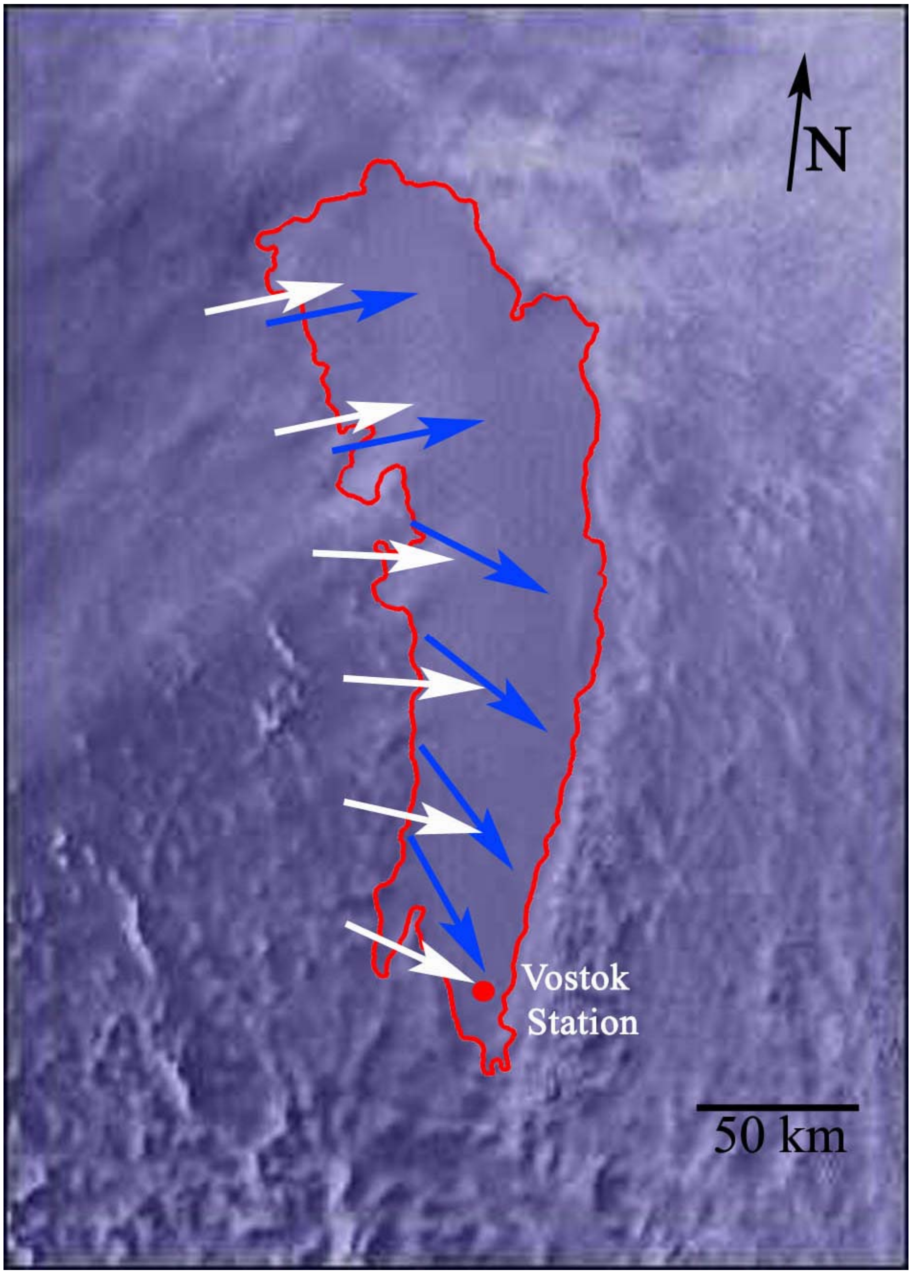


Figure 2.1 Radarsat satellite image over Lake Vostok. The red line outlines the lake's coast defined from radar sounding (see section 2.5). Vostok Station is marked by the red circle. The white arrows show the direction of the ice flow derived from inSAR analysis (from Kwok et al., 2000). The blue arrows show the ice flow field inferred from radar sounding structure tracking (Tikku et al., 2004). The maximal discrepancy between these two ice flow directions is 30º in the southern part of the lake.

be observed from an aircraft when it is at some distance from the flat areas and the view angle is relatively small, so those areas appear to be darker than the surroundings. He referred to those areas as “lakes”. Those “lakes” were very consistent in their location, so Russian pilots used them for the navigational purposes.

In the 1950s and 1960s theoretical calculations were made (Kapitsa et al., 1996 and references therein) suggesting that high overburden pressure at the bottom of a thick ice sheet is created, so the temperature at the bottom of may be close to the pressure melting point. These calculations suggested that the temperature at the bottom of the ice is -2ºC while the pressure exceeds 300 atmospheres in the area of Vostok station (Zotikov et al., 2000 and references therein). At similar temperature and pressure conditions, the ice is at its melting point. This melted water may collect in the local depressions beneath the ice, forming subglacial lakes under the thickest portions of the Antarctic ice.

The first direct evidence of water beneath the ~4 km thick ice sheet of East Antarctica in the vicinity of Vostok Station was uncovered during the airborne radar sounding survey performed collaboratively by the United States Antarctic Program and the Scott Polar Research Institute (SPRI, Cambridge, UK) in early 1970s (Oswald and Robin, 1973). Unusually high amplitudes of the radar sounding returns were recorded over several relatively large spots, suggesting the presence of water beneath the ice. This characteristic brightness of the radar signal is used as one of the primary indicators of subglacial lakes (Oswald, G.K.A., and G. de Q. Robin, 1973; Carter et al., 2007).

Another piece of evidence appeared in 1993 when satellite altimetry data over Antarctica became available (Ridley et al., 1993). The satellite data revealed the extensive flat area in the vicinity of Vostok Station (Figure 2.1) that coincided with the bright reflections observed by Oswald and Robin. Thus the hypothesis was developed about the existence of the large subglacial lake in the area of Vostok Station, which was named Lake Vostok.

The final proof of the presence of water beneath the Vostok Station appeared in 1996 when the Russian scientist Kapitsa reinterpreted one of the seismograms he recorded at Vostok Station in 1964 (Kapitsa et al., 1996). The recorded seismogram shows the second reflection after the ice-water echo, which was initially interpreted as the bottom of a sedimentary layer beneath the ice sheet. The revised interpretation suggested that this reflection indeed came from the bottom of the lake, revealing the water thickness of 510 m beneath Vostok Station (Kapitsa et al., 1996).

2.2 Ice flow over the lake

The data on ice flow over Lake Vostok are controversial. The first direct measurements of the velocity and direction of ice motion at Vostok Station by star sites were made in 1960s that gave the ice velocity of 3.7 ± 0.7 m/yr with the azimuth of $142 \pm 10^{\circ}$ with respect to true north (Kapitsa et al., 1996). Another direct measurement (GPS) is reported by Bell et al. (2002) as 3.0 ± 0.8 m/yr at $131 \pm 4^{\circ}$ relative to true north.

The ice motion over the entire lake area was measured using repeat-pass synthetic aperture radar (SAR) interferometry (Kwok et al., 2000; white arrows in Figure 2.1), suggesting the ice motion at Vostok Station of 4.2 m/yr. Overall, the inSAR measurements show that the regional ice flow over Lake Vostok is from west to east, perpendicular to the surface elevation contours with the faster surface velocity in the southern part of the lake.

Another estimate for the ice flow field over the entire lake area was performed by Tikku et al., 2004 by the analysis of airborne radar data. The structure tracking for three different internal layers of radar sounding data (blue arrows in Figure 2.1) show the disagreement of ~10˚ with the flow direction derived from inSAR (Kwok et al, 2000) in the center of the lake. The angular difference between the inSAR and structure tracking (Tikku et al, 2004) increases up to ~30˚ in the southern part of the lake. Tikku et al. (2004) explains this discrepancy with the errors in the inSAR flow field. The structure tracking also gives smaller amplitudes of ice velocity (~ 2 m/yr) at Vostok Station. Overall, the flow field derived by structure tracking "displays the gradual rotation in the flow direction, from W-E in the northern end to NNW-SSE in the southern end" (Tikku et al., 2004).

2.3 The data from the ice core 5G-1 at Vostok Station

The drilling of the ice core 5G-1 at Vostok station started in 1967. The ice thickness beneath Vostok station was measured to be 3750 m by radar and seismic soundings. For almost three decades (until 1998) the drilling has been conducted until it reached the depth 3623 m. The ice samples from the 5G-1 ice core revealed the climate history for more than 420 thousand years, showing at least four glacial and interglacial periods (Petit et al., 1999).

The isotope studies of the samples from the ice core at Vostok station show that the ice below a depth of 3539 m is frozen (accreted) from the lake water onto the base of the ice sheet (Jouzel et al., 1999). This layer of the accreted ice is 211 m thick. The first 70 m of the lake ice (at the depths 3539 – 3609 m) contains visible solid inclusions, which are "millimetric in size and consists of a mineral particle to which dirt is attached" (Jouzel et al., 1999). This upper 70 m thick portion of the accreted ice is referred to as "muddy ice" (Leitchenkov et al., 2007). The visible inclusions observed in the samples of the accreted ice are generally of two types (Leitchenkov et al., 2007; Figure 2.2).

a.

b.

c.

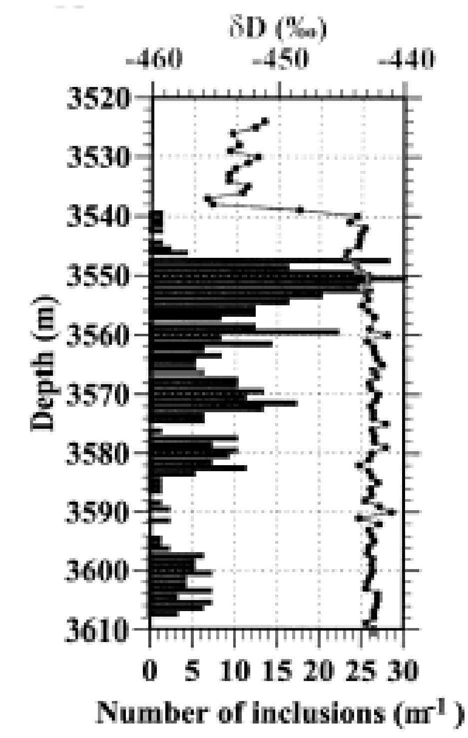


Figure 2.2. Sediment inclusions in the accreted ice from the borehole at Vostok Station

a. Soft aggregates, mostly clay in content (photo from Leitchenkov et al., 2007);
b. Solid inclusions are a few millimeters in size (photo from Leitchenkov et al., 2007);
c. The total number of visible inclusions in the accreted ice (reprinted from Souchez et al., 2000, with the permission from Elsevier). The sharp change in deuterium excess (δD) at the depth of 3539 m marks the transition zone between the atmospheric and accreted ice.

The majority of those inclusions are the soft aggregates, composed mostly of the clay minerals (Leitchenkov et al., 2007; Figure 2.2.a). The second type of inclusion consists of the larger ‘solid’ particles that “mainly consist of the rock core on which the dirt particles are attached” (Souchez et al., 2002; Figure 2.2.b). The number of such inclusions is significantly smaller, but their dimensions are up to 4.5 mm in length (Leitchenkov et al., 2007). The total number of visible inclusions increases dramatically in the top section of the “muddy ice”, counting up to 30 inclusions per one meter of the core (Souchez et al., 2002; Figure 2.2.c).

“Muddy ice” also contains some amount of microscopic particles (up to 30 μm, mostly clay in content) that are believed to have been suspended in the lake’s water (Royston-Bishop et al., 2005). The major axis length of those particles is reported to be between <1 and 45 μm with an average of 6.7 μm (Royston-Bishop, 2005).

The “muddy ice” is believed to be formed as sediments were scoured by the moving ice while the ice crosses the small embayment in the south-western part of the lake (Leitchenkov et al., 2007; see Figure 2.1). The inclusions got incorporated into the accreted ice over the embayment that is considered to be the shallow portion of the lake, while the deeper clear ice was refrozen from the deep water. Leitchenkov et al. (2007) support this hypothesis with the fact that the length of the shallow portion of the lake is about 1/3 of the total ice flow distance; therefore the inclusions are observed in the upper 70 meters out of ~210 m thick accreted ice.

Some microorganisms were found in the samples of accreted ice (Karl et al., 1999), indicating that Lake Vostok is a unique, cold and lightless environment supporting life. At the depths between 3551 and 3607 m in the 20 - 15 ky old accreted ice the presence of some thermophilic bacteria was identified (Bulat et al., 2003 and 2004), inferring that there is a geothermal system beneath Lake Vostok. Bulat et al., (2003) postulate the presence of "deep crustal faults within the lake bedrock. Seeping solutions from the crust encouraged by rare seismotectonic events boost hydrothermal plume and may flush out 'crustal' bacteria and mineral products up to their vents. Some of them are likely open in a shallow bay upstream Vostok where microbes and sediments may steadily be trapped by a rapid process of accretion" (Bulat et al., 2003).

However, the presence of life in Lake Vostok remains questionable since some of microbes found in the accreted ice "may originate from contamination during the sample collection, retrieval and processing procedure" (Priscu et al, 2005).

Since 1998 the drilling has stopped at a depth of 3623 m, which is ~ 120 m above the ice/water interface, to avoid possible contamination of the lake water by drilling fluid (Petit et al., 1999).

2.4 Seismic soundings over Lake Vostok

Since 1995 seismic soundings in the Lake Vostok area have been undertaken jointly by the Polar Marine Geological Research Expedition (PMGRE) and the Russian Antarctic Expedition (RAE). Overall, more than a hundred soundings performed along six seismic profiles (Figure 2.3). "Signals were recorded by 600 and 1200 m long, 24 channel linear arrays with 25 and 50 m intervals between geophones. The distance from the shot points to the first geophone averaged 3.5 – 4.0 km and reached maximum of 11 km. For generation of acoustic waves, an explosive cord was laid out in parallel arrays, each consisting of 2 to 10 lines 50 – 75 m long. The overall weight of explosive in a single shot-point ranged from 2.5 to 5 kg" (Masolov et al., 1999).

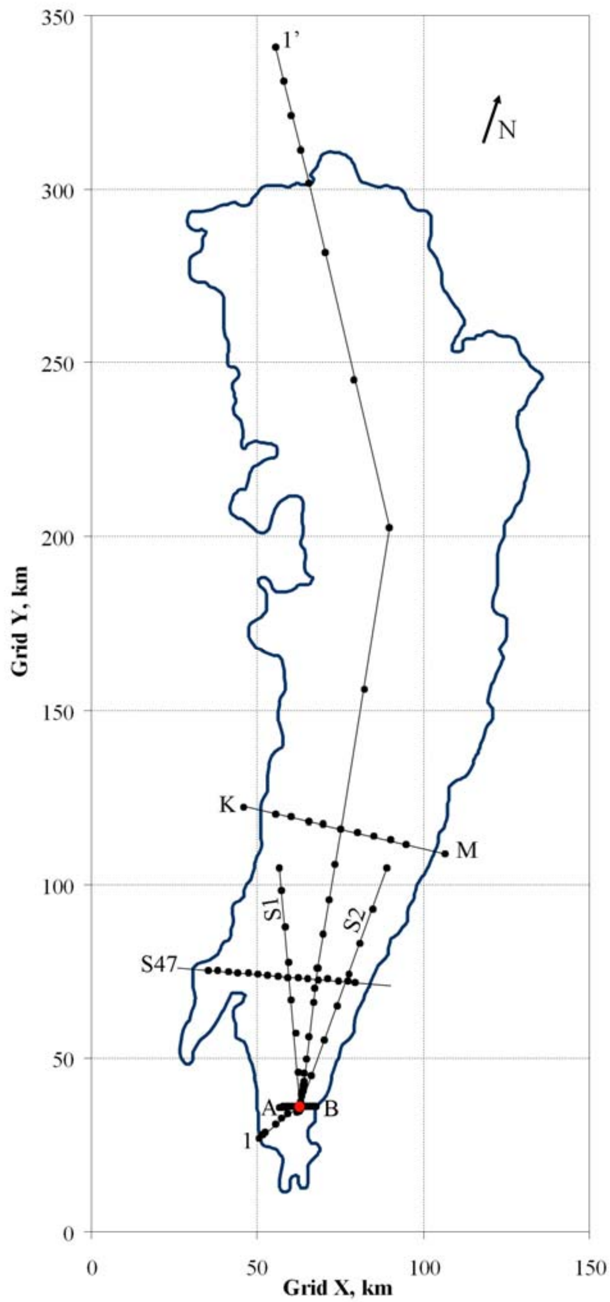


Figure 2.3 The location of seismic profiles (black lines) acquired over Lake Vostok. Black dots show the location of seismic soundings. Three of these profiles are named based on their start and end points (AB, KM and 1-1'). The other three are named S1, S2 and S47. The blue line outlines the lake based on the results of airborne radar sounding (see section 2.5). The red dot shows the location of Vostok Station.

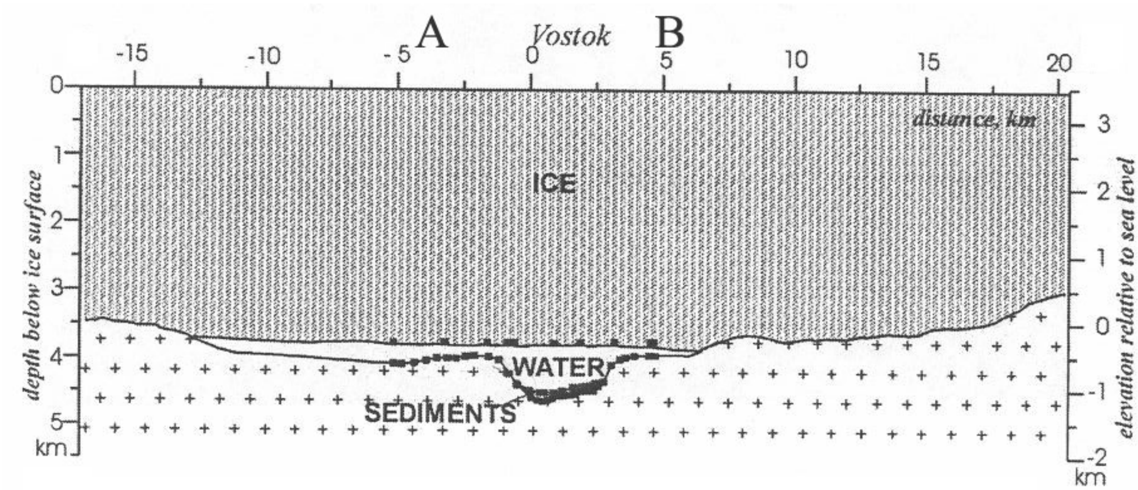
Seismic soundings revealed the water depth and the sediment thickness in Lake Vostok (Masolov et al., 1999; Item CEP 4c, 2002). To date six seismic profiles are published (Figure 2.3). Those profiles have a rather complicated naming scheme. The first three profiles published in 1999 (Masolov et al., 1999) have been named based on their starting and ending points, e.g. profiles AB, KM and 1-1' in Figure 2.3. The cross-sections along those lines include ice, water and unconsolidated sediments layers (see profile AB in Figure 2.4.a). The latter was interpreted to be up to 350 m thick with the assumed seismic velocity of 2650 m/s (Masolov et al., 1999).

The rest of the seismic lines are named S1, S2 and S47. Profiles S1 and S2 were released in 2002 (Item CEP 4c, 2002) along with the revised profiles AB, KM and 1 – 1'. The revised cross-sections show 40 - 110 m of unconsolidated sediments at the lake's bottom with an assumed velocity of the seismic waves of 2500 m/s (see profile 1-1' in Figure 2.4.b).

The cross-section for the last profile – S47 – was published in 2006 (Masolov et al., 2006; Figure 2.5), showing that the water layer overlies the acoustic basement. This new interpretation of seismic data implies that the reflections that used to be interpreted as the bottom of the sediments are reinterpreted to be side echoes from the rough lake's bottom (Popkov, 2005 – personal communication), implying that there are no sediments at the bottom of Lake Vostok.

Overall, seismics suggest that the southern part of the lake has a water thickness of up to 1200 m (~40 km of profile S47, Figure 2.5), while water thickness decreases to 250 m in the northern part of the lake (Profile 1-1', Figure 2.4.b). The seismic data reveal a relatively small (about 5 km across) and deep (up to 680 m) basin at southern part of the lake in the vicinity of Vostok Station (Profile AB, Figure 2.4.a). Earlier interpretation of

a.



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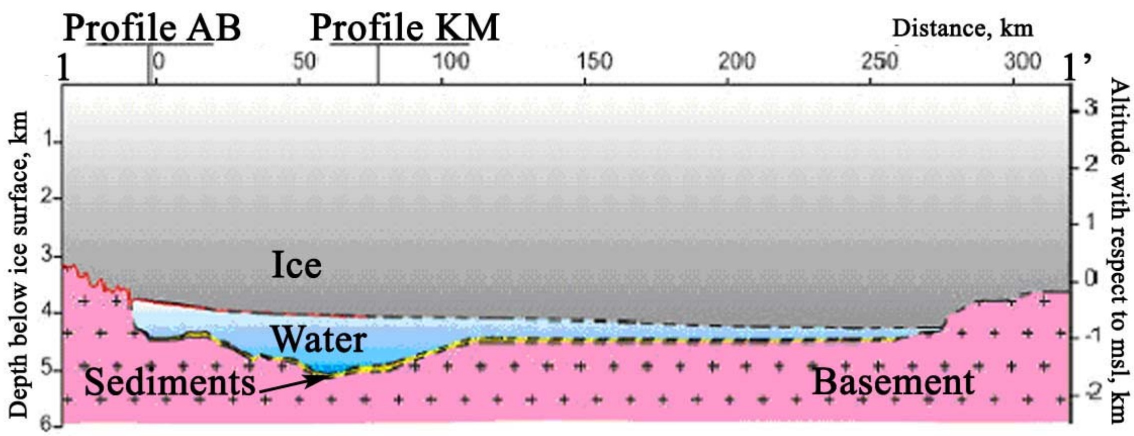


Figure 2.4 The results of joint interpretation of ground-based radar sounding and seismic data along profiles AB and 1-1'. For the location see Figure 2.3.

a. The cross-section along the profile AB (from Masolov et al., 1999);
b. The cross-section along the profile 1-1' (adopted from Item CEP 4c, 2002) showing the 40 -100 m thick layer of unconsolidated sediments at the bottom of Lake Vostok.

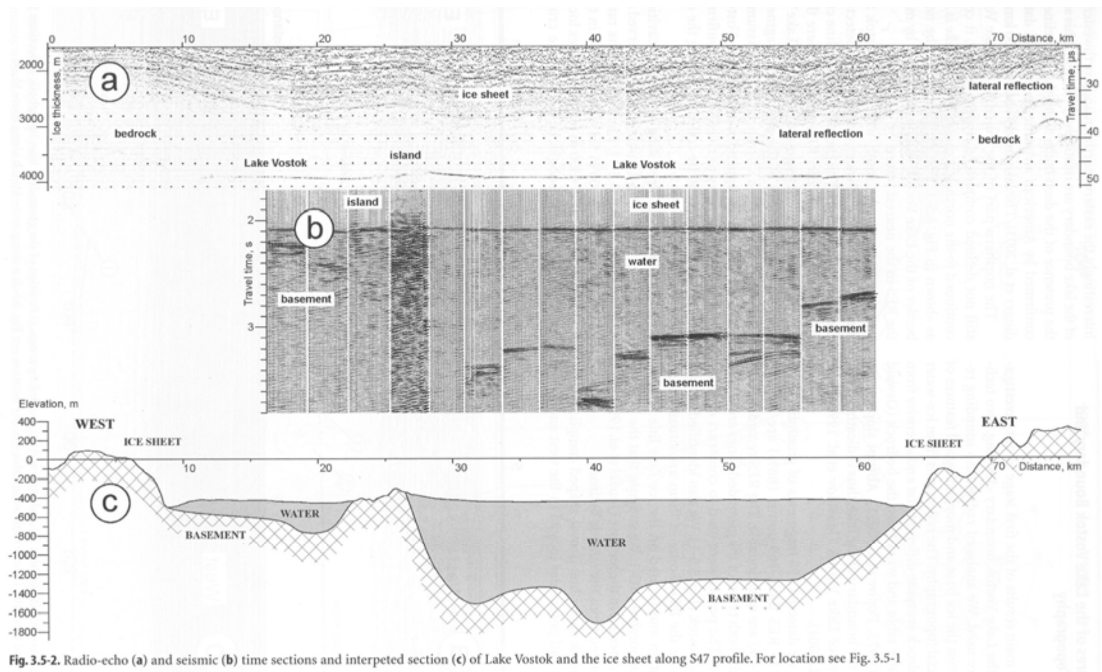


Figure 2.5 The results of joint interpretation of ground-based radar sounding and seismic data along profile S47 (from Masolov et al., 2006; reprinted with the permission of Springer):

a. The results from ground-based radar sounding;
b. Seismic soundings time sections along the profile; the horizontal scale is the same as in sections a. and c. The location of the individual soundings are shown as black dots in Figure 2.3;
c. The interpreted cross-section along the profile S47 showing the water layer overlying the basement, inferring the absence of unconsolidated sediments at the bottom of Lake Vostok.

seismic data suggested that this basin was filled with 350 m of sediments (Masolov et al., 1999).

2.5 Airborne geophysical surveys over Lake Vostok

The airborne geophysical survey over Lake Vostok was performed by the University of Texas Institute for Geophysics (UTIG) during the 2000-2001 field season (Richter et al., 2001 and 2002; Studinger et al., 2003a; Holt et al., 2006).

The survey block over Lake Vostok was 165 by 330 km. Each survey line was separated by 7.5 km with tie lines spaced between 11.25 and 22.5 km. The average altitude of the aircraft was 3.96 km above mean sea level. The collected geophysical data included gravity, magnetics, radar sounding and laser altimetry (Figure 2.6).

The radar sounding signal over the ice-water interface has a distinctive high amplitude (Figure 2.7.a), allowing mapping of the lake's coast line (Sasha Carter - personal communication; Figure 2.7.b). The ~200 m-thick layer of accreted ice at the base of the ice sheet corresponds with the reflector on radar profiles in the southern part of the lake (Figure 2.7.a); there is no evidence of this layer in the northern part of the lake implying that melting is occurring there (Siegert et al., 2000 and 2001; Falola and Oliason, 2001; Bell et al., 2002; Figure 2.7.b). The recorded gravity over LVS was reduced to the free-air anomaly with an estimated precision of 1.2 mGal (Richter et al., 2001 and 2002; Holt et al., 2006). The accuracy of the magnetic anomaly is estimated to be 4.8 nT (S. Kempf – personal communication).

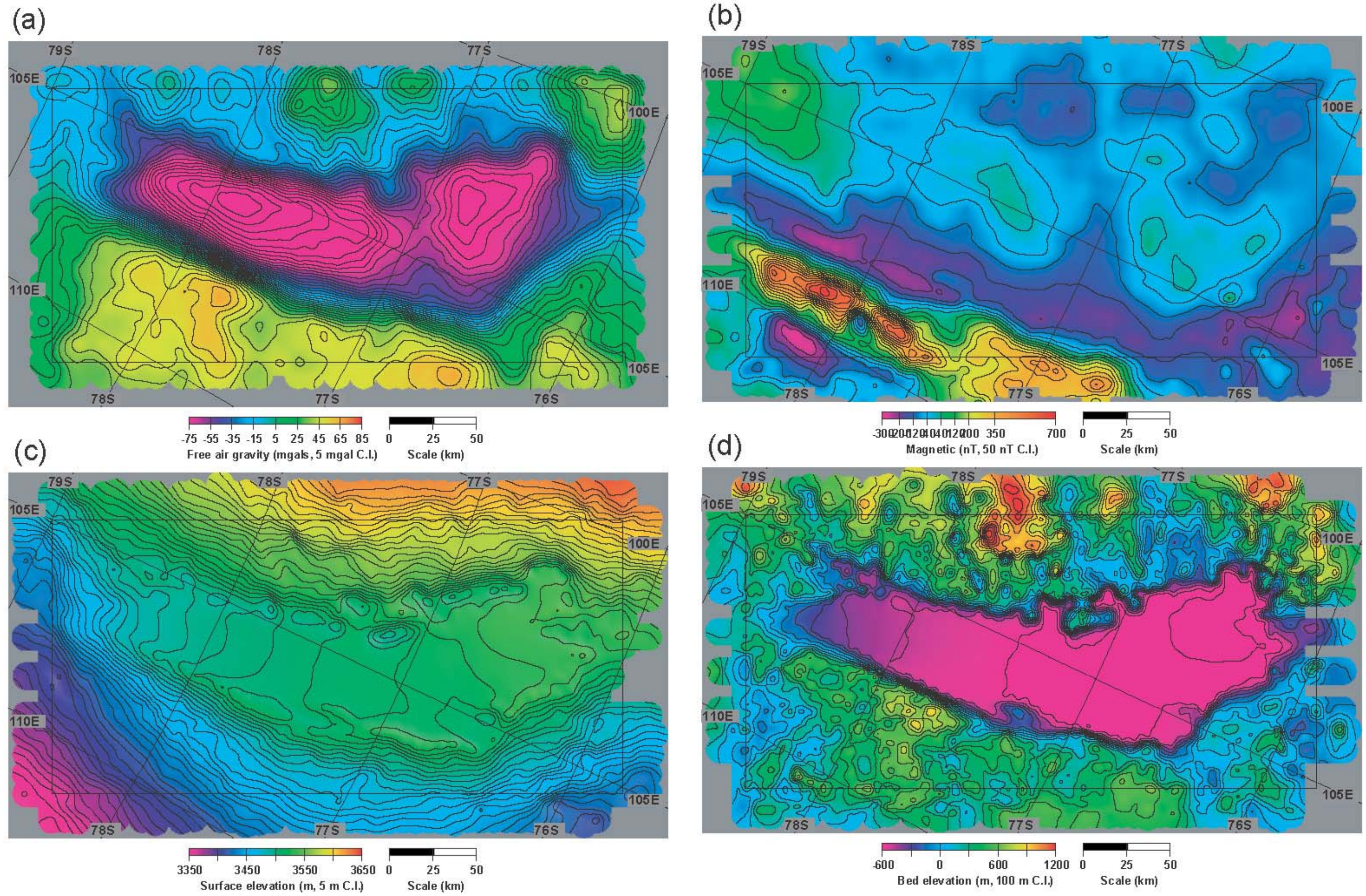
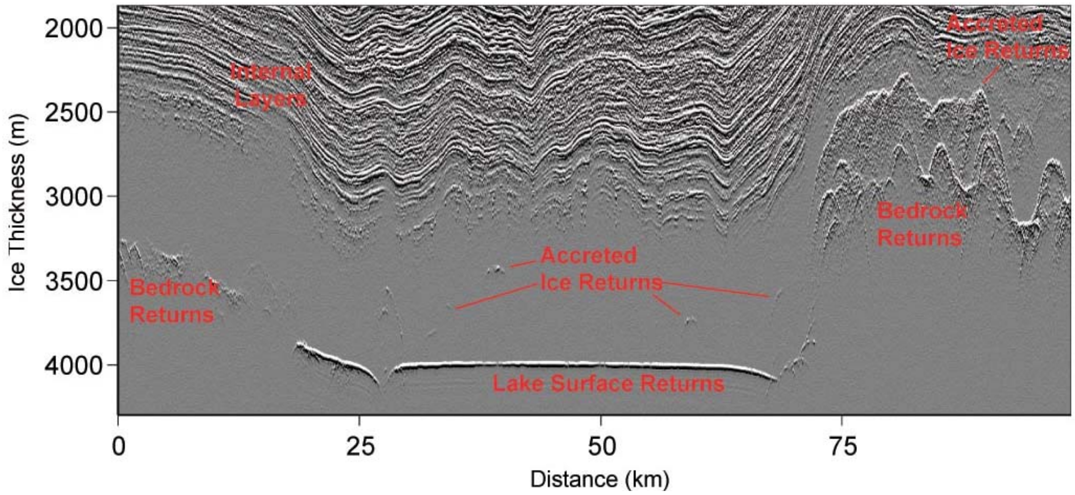


Figure 2.6 Results of the UTIG airborne geophysical survey over Lake Vostok (data from http://www.ig.utexas.edu/research/projects/soar/data/LVS/SOAR_lvs.htm)

a. Free-air gravity, mGal; b. Magnetic data, nT; c. Surface elevation, m above msl; d. Ice thickness, m

a.



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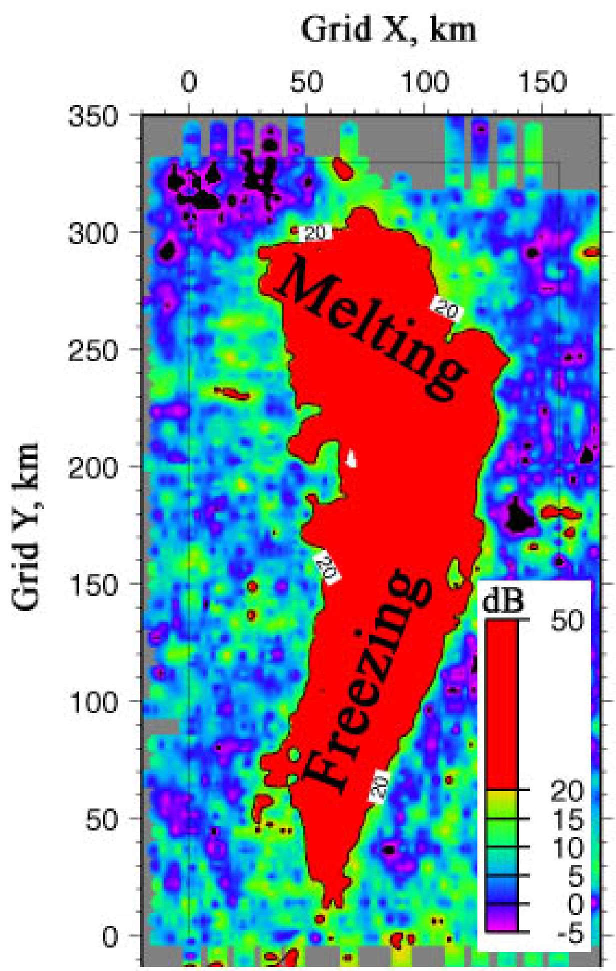


Figure 2.7 Radar sounding data over subglacial Lake Vostok

a. A radar profile over the southern portion of the lake, showing the bright echo associated with the ice-water interface and the accreted ice returns (D. Blankenship, personal communication);
b. The radar sounding bed echo strength map (Sasha Carter, personal communication).
The bright echo outlines Lake Vostok, The ice sheet in the northern part of the lake is melting, while the larger southern portion is dominated by freezing of lake's water at the bottom of the ice (see text).

2.6 The water exchange between Lake Vostok and the overlying ice sheet

Both seismic (Masolov et al., 1999) and radar soundings over Lake Vostok show that the overlying ice sheet is ~400 m thinner in the southern part of the lake compared to its northern part (Figure 2.6.d). This north-plunging ice ceiling over the lake creates different temperature/pressure conditions over the lake, that trigger melting and freezing at the ice-water interface (Figure 2.7.b). The southern part that is covered with thinner ice is subject to lake's water freezing at the bottom of the ice sheet, while the ice in the northern part of the lake is thick enough to be at the melting point at its bottom. This distribution pattern of melting and freezing indicates that significant exchange of water between the lake and the overlying ice occurs in Lake Vostok. This exchange of mass and heat leads to water circulation, since colder and denser meltwater from the northern part of the lake sinks and is transported horizontally to the south, where the pressure-melting point is higher and refreezing occurs (Kapitsa et al., 1996; Siegert et al., 2000; Thoma et al., 2007).

Estimates for the rates of those internal processes were made by Siegert et al. (2000) based on the combined analysis of SPRI airborne radar sounding data from 1970's and inSAR ice flow measurements (Kwok et al., 2000). The analysis of Siegert et al. (2000) shows that the freezing rates in the southern part of Lake Vostok vary between ~2 and ~6 cm/yr with the increase of freezing rate toward the south end of the lake. The estimate for the melting rate in the northern part of the lake showed the maximal value of ~38 cm/yr at 1 km downstream of the grounding line and decreased to ~ 2 cm/yr by 8 km from the grounding line.

2.7 Hypotheses for the origin of Lake Vostok

Water for most of subglacial lakes in Antarctica is believed to originate in the areas where the geothermal heat and the insulation of the overlying ice sheet are sufficient to maintain the basal temperature at the pressure melting point (Carter et al., 2007). The melted water is collected in local depressions forming small and most likely shallow subglacial lakes (Siegert et al., 2005). Kapitsa at al., (1996) proposed that this melting of the overlying ice is the source of the water in subglacial Lake Vostok, implying that the lake was formed after the current ice sheet covered the lake.

Another hypothesis appeared in 2001 postulating that the lake could exist before the ice sheet came, suggesting that Lake Vostok may be over 5-30 Myr old (Duxbury et al., 2001). Duxbury et al (2001) performed numerical modeling showing that if the depth of the lake before the glaciation was only 53 m, the lake would survive the following glacial period without being frozen to the bottom.

The water thickness in Lake Vostok is known to exceed 1000 m (Item CEP 4c, 2002), so the numerical modeling of Duxbury et al. (2001) infers that the lake may be of pre-glacial origin. This has been criticized by Siegert (2005), suggesting that the modeling of Duxbury et al (2001) was based on the assumption of Lake Vostok being a closed system, while this is not the case during the onset of glacial period. Siegert (2005) proposes that even if the lake existed before the glacial advance, it would be completely frozen during the onset period of glaciation. This conclusion is based on the water pressure gradient dictated by the overlying ice. The ice sheet modeling performed by Siegert (2005) suggests that during the initial 6000 years of glaciation the water pressure gradient of Lake Vostok "is likely to be high enough to remove subglacial water", concluding that the lake should be overridden by grounded ice during the onset of the glacial period. He also notes that although the lake's trough must be occupied with the grounded ice during the period of ice growth, this "does not rule out the possibility … of ancient lake sediments being present within the lake" (Siegert, 2005). Thus, whether Lake Vostok existed before glaciation or it was formed after the ice advance is still subject for substantial debate.

2.8 Tectonic framework for Lake Vostok

The tectonic framework for Lake Vostok is still a subject for debate. There are two dominating hypothesis about tectonic settings of the lake. One model, developed by Studinger et al. (2003b), suggests that Lake Vostok is associated with a tectonic boundary within East Antarctica that resulted from a thrust sheet emplacement onto an earlier passive continental margin. This tectonic event possibly took place in the Proterozoic. The formation of Lake Vostok is hypothesized to be the result of minor normal faulting associated with reactivation of the trust sheets.

Another model, proposed by Leitchenkov et al. (2003 and 2005), postulates that Lake Vostok represents a typical extensionally-induced intracontinental rift zone. The rift graben of Lake Vostok is considered to be a part of a spacious rift system with the main arm "stretched from the Prydz Bay through the Lambert Glacier and the eastern foot of Gamburtsev Mts. to, at least, 110E. This rift system is a result of large-scale extensional event, which occurred in East Antarctica in Late Jurassic – Early Cretaceous prior to East Gondwana break-up." (Leitchenkov et al., 2003)

Both of those hypotheses imply the presence of a several kilometer thick sedimentary basin beneath Lake Vostok. The model of Studinger (2003b) shows that this basin is up to 5 km thick and filled with sedimentary rocks with density of 2500 kg/m^3. Leitchenkov et al. (2005) suggest the presence of a several km thick sedimentary basin that is inferred from the analysis of older gravity data recorded from just a few tens of points over the lake area.

Chapter 3: 2D and 3D inversions of airborne gravity data over subglacial Lake Vostok

3.1 Motivation and objectives for the study

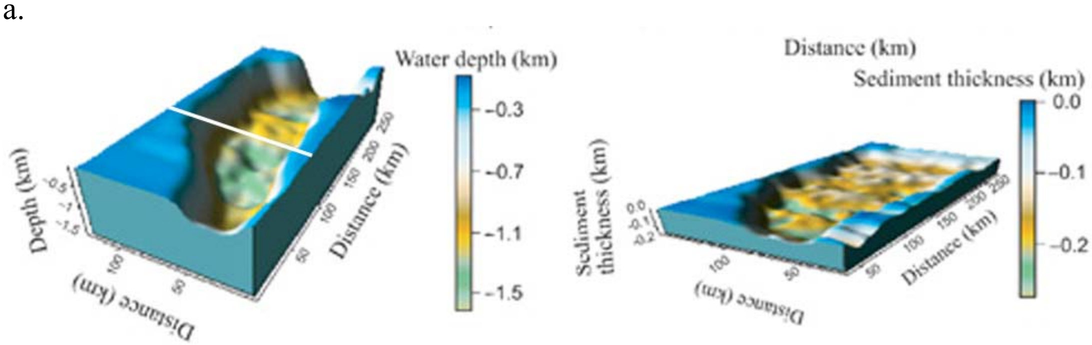
Subglacial lakes in Antarctica are relatively new objects for research. Most of them were discovered within the last decade with the exception of subglacial Lake Vostok, which has been known since the 1970s. Because Lake Vostok is significantly larger than all other known subglacial lakes in Antarctica, major research efforts have been focused on this lake. Both seismic and radar sounding have shown that the ice over the southern part of the lake is several hundred meters thinner than in the northern part. This north-dipping lake ceiling causes the temperature/pressure conditions at the ice bottom to vary across different parts of the lake (Kapitsa et al., 1996; Siegert et al., 2000 and 2001; Studinger et al., 2003a). Those differences trigger melting at the ice-water interface in the northern part of the lake but freezing of the lake water onto the bottom of the ice sheet in the southern part of the lake. Such a distribution of melting/freezing patterns, in turn, is responsible for generating water circulation within the lake (Siegert et al, 2000 and 2001; Thoma – personal communication, 2007).

All of the internal processes within subglacial lakes are subject to numerical modeling, as in Thoma et al., 2007. The key 'a priori' information for such modeling is the 3D geometry of the lake, which infers both spatial and depth distribution of water as well as unconsolidated sediments at the bottom of the lake. The ultimate goal for this research was to develop 3D bathymetry models and sediment distributions for both Lake Vostok and Lake Concordia via inversion of airborne gravity data collected by the University of Texas Institute for Geophysics (UTIG) in the 1999-2000 and 2000-2001 field seasons.

The research presented in this Chapter consists of two major parts. The first portion comprises 2D inversion of airborne gravity data over Lake Vostok. The primary objective of the 2D inversion was to find the "host rock" density that gives the best correspondence with observed seismic data. 2D modeling was completed in 2003 and presented on the IX International Symposium on the Antarctic Earth Sciences in Potsdam, Germany in September 2003 (Filina et al, 2006a), as well as at the AGU Fall meeting in 2003 (Filina et al., 2003). At that time, the only other bathymetry model of Lake Vostok was developed via inversion of the same airborne gravity dataset. (Roy et al., 2005, submitted in 2003; Figure 3.1.a). This model shows the deepest lake bottom at ~1550 m below sea level (corresponding to ~800 m of water thickness) and sediment thickness of 300 m in the northern basin. In the Roy et al. (2005) model, the ice and water were considered to be one layer due to their similar densities. The different densities of the host rocks were used (2600 kg/m^3 for the lake's cavity area, 2800 kg/m^3 east of the lake) to represent the presence of the thrust fault suggested by Studinger et al. (2003). Roy et al. (2005) used the sediment density of 2000 kg/m^3. They chose the regional trend, required to calculate the residual anomaly before inversion, to be linear. The inversion was performed using the Very Fast Simulating Annealing algorithm (Sen and Stoffa, 1995). However, this model has significant discrepancy with seismic data, as well as spatial divergence with the coastline obtained from radar sounding data (Figure 3.1.b).

The major objective for the second portion of this study was to develop 3D bathymetry model of Lake Vostok. The results of this part of my research were presented as a poster in the First Scientific Committee on Antarctic Research (SCAR) Open Science Conference in Bremen, Germany, in July 2004 (Filina et al., 2004).

a.



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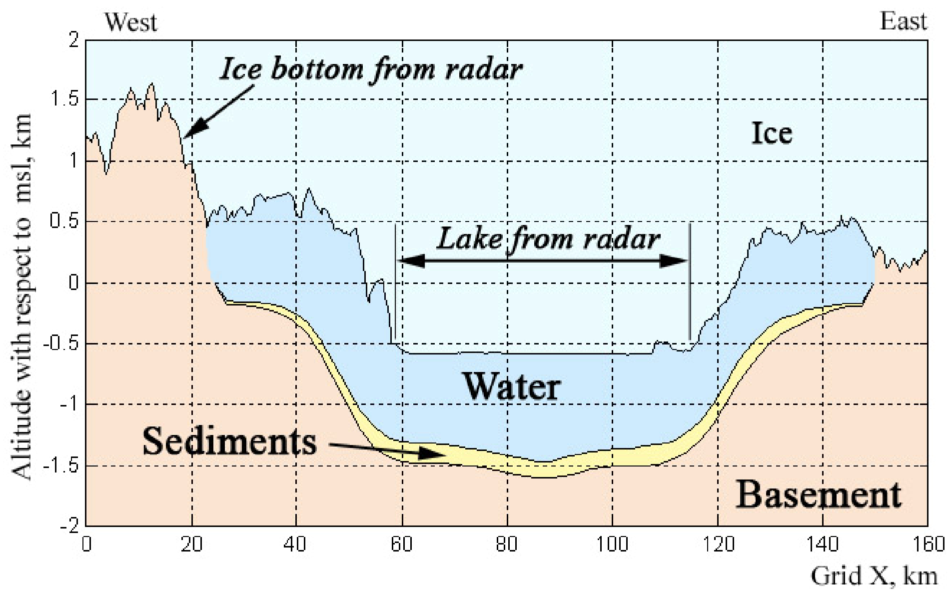


Figure 3.1 3D bathymetry model and sediment distribution from the model of Roy et al., 2005

a. The water depth (with respect to m.s.l.) and sediment thickness of Lake Vostok (from Roy at al., 2005); white line shows the location of the profile shown in section b of this Figure;
b. The comparison between radar sounding data over Lake Vostok and the model of Roy et al., 2005, showing the spatial discrepancy of the Roy et al., 2005 model with the lake's coastline.

3.2 The data used in the study

This study uses the airborne gravity dataset collected by UTIG during the 2000-2001 austral summer (Chapter 2; Richter et al, 2001 and 2002; Studinger et al, 2003a; Holt et al., 2006) over Lake Vostok. The ice thickness known from radar sounding combined with the laser altimetry reveals the elevations of both ice surface and ice bottom with respect to WGS-84 mean sea level (msl). A radar sounding echo-strength map outlines the coastline of Lake Vostok (Figure 3.2; Sasha Carter, personal communication). The airborne gravity data were reduced at UTIG by Thomas Richter and others (Richter et al., 2001 and 2002; Holt et al., 2006). The reported RMS of the differences at the crossover points for the gravity grid after leveling is 1.2 mGal (Holt et al., 2006).

Before the inversion, the gravity data over the lake were reduced to sea level, i.e., the gravity effect from all the material above sea level (ice and bedrock) was calculated (see forward problem section below) and subtracted from the free-air gravity anomaly.

The gravity anomaly increases rapidly by about 70 mGal — from the western edge to the eastern edge of the lake basin (Figure 3.3). Such a sharp increase in gravity indicates a significant change in the lower crust from west to east of the lake. To remove the gravity effect from deeper geological structures, a regional trend should be found for each profile. Such a trend should meet the following criteria:

(1) it should coincide with the residual anomaly outside of the lake area;

(2) it should be as close as possible to the linear over the lake;

(3) it should consist of only low frequencies due to deep sources.

In the case of 2D modeling, the trend was found for each 2D line by cubic spline interpolation (Figure 3.3.a). To find the 3D regional trend, the anomaly outside of the lake was complemented by 2D trends found by cubic spline interpolation along several

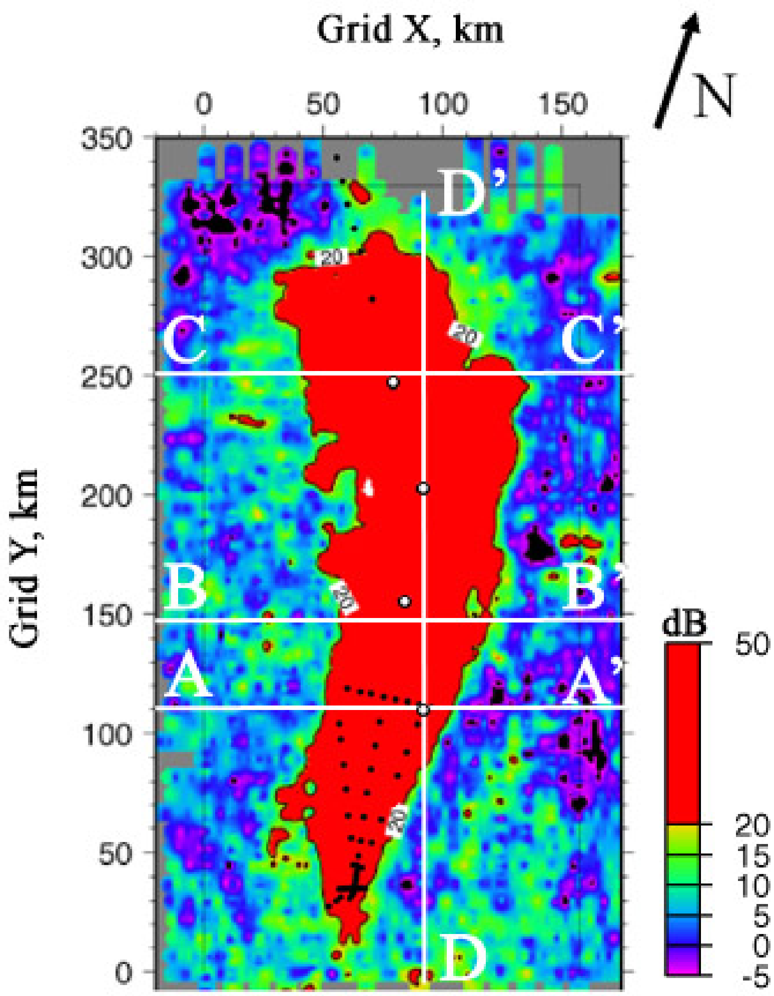
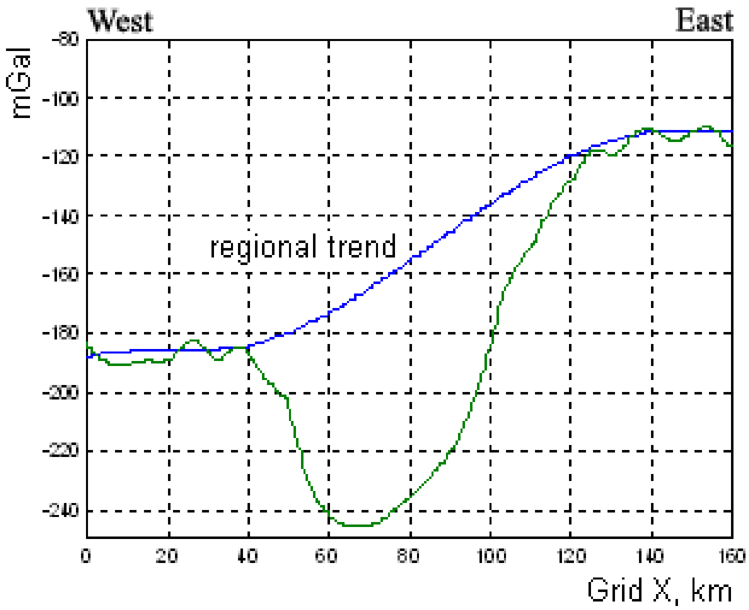


Figure 3.2 Radar sounding bed-echo-strength map of Lake Vostok area (Sasha Carter, personal communication). White lines are profiles for 2D inversion. The open circles show the location of seismic soundings used to constrain 2D modeling (blue arrows in Figures 3.4 – 3.6). Black dots are seismic soundings from Masolov et al. (1999) and Item 4c (2002).

a.



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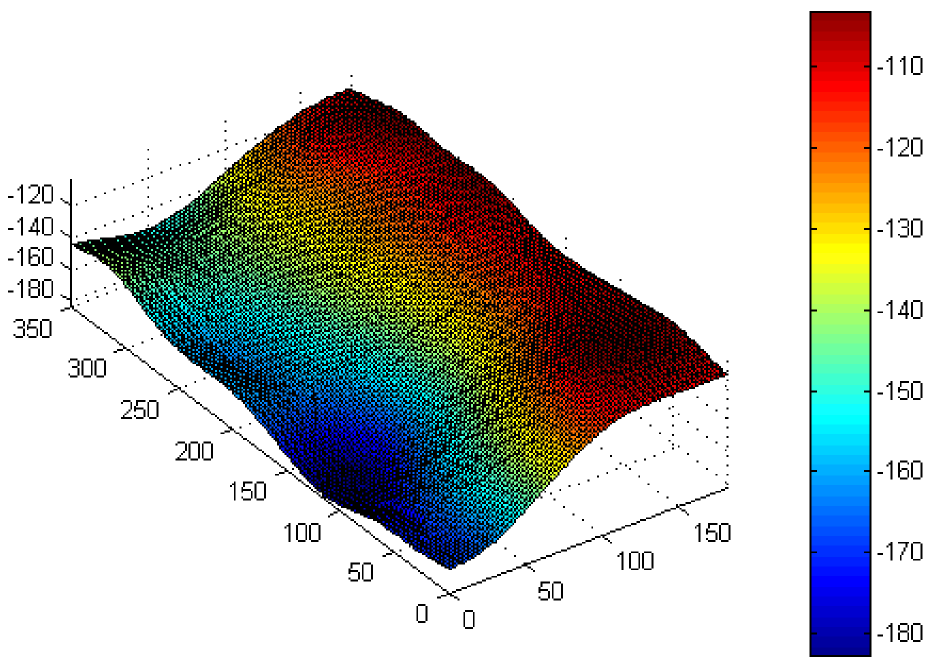


Figure 3.3 Regional trend of gravity data over Lake Vostok

a. Regional trend for profile A-A' (see Figure 3.2 for the location of the profile);
b. Regional trend in 3D for entire lake region.

profiles spaced by 50 km. The resultant regional trend was found by interpolation over the entire lake region, followed by the low-pass filtering with a 50 km wide window (Figure 3.3.b).

3.3 Forward and inverse problems

The forward problem in 2D was solved using Talwani's method for calculation of a gravity anomaly due to a 2D body with a polygonal cross section (Grant and West, 1965; Appendix 1). The densities of ice and water are close, so the ice and water of the lake are considered as one layer (950 kg/m^3, as in Roy at al., 2005). The density contrast along a profile was assumed to be constant. Inversion was performed for a two-layered model, which consisted of ice/water and sediment layers overlying the dense bedrock. The water depth then was found by subtracting the ice thickness, measured by radar sounding, from the total thickness of ice/water layer. The coordinates of these bodies' vertices were chosen as model parameters. The locations of the lake and the ice thickness/subglacial topography, known from radar sounding, were used to constrain the model. Also, the 2D model for Lake Vostok was constrained by water and sediment thicknesses known to date from seismic data (Masolov at al., 1999; open circles in Figure 3.2). More seismic data became available by the time the 3D modeling was performed.

Inversion was performed using a conjugate gradient algorithm (Tarantola, 1987) for several fixed values of density contrast between the ice/water body and the surrounding rock. The density contrast between sediment and host rock is chosen to be -700 kg/m^3, as in Roy et al. (2005). The thickness of sedimentary layer was forced not to deviate more than 30% of the measured value in the adjacent seismic point (open circles in Figure 3.2; marked by blue arrows in Figures 3.4 – 3.6).

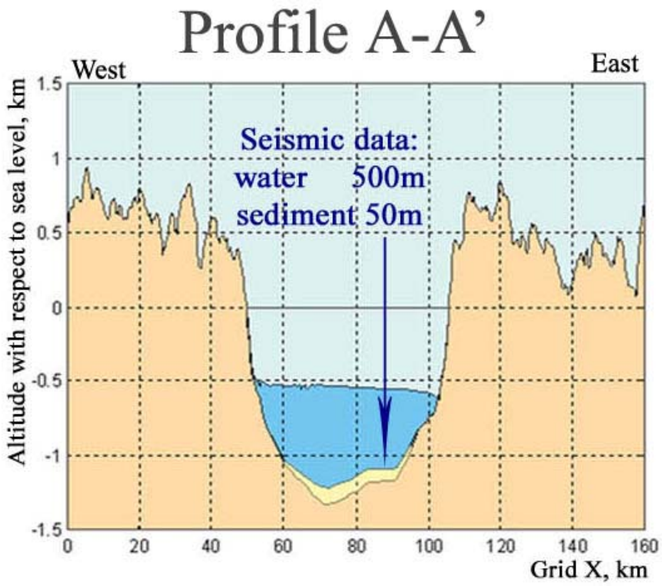
In the case of 3D modeling, the ice (density of 920 kg/m^3), the water (1000 kg/m^3) and unconsolidated sediments (assumed density of 1850 kg/m^3) were composed of a number of rectangular prisms of various sizes. The gravity effect of every prism was then calculated assuming the density contrast between those layers and the host rocks to be constant in the survey area, using the equation of Nagy et al., 2000 (Appendix 2). The 3D inversions were also performed by a conjugate gradient algorithm for several fixed densities of the host rock (Tarantola, 1987).

3.4 The results of gravity inversion over Lake Vostok: 2D case

Four profiles over Lake Vostok were chosen for gravity modeling (Figure 3.2). The best agreement of the 2D gravity model with the results of seismic interpretation at the coincident point on profile A–A' (see Figure 3.4) was achieved for a density contrast of -1600 kg/m^3 between ice/water and host rock, which corresponds to a bedrock density of 2550 kg/m^3 (with an ice/water density of 950 kg/m^3). The calculation over other profiles was performed using this value of density contrast. The result over profile A-A' shows a maximum water thickness of 750 m; the maximum sediment thickness is 120 m. The difference with seismic results at the cross-over point for both water and sediment layers are within 50 m.

The results over profiles B-B' and C-C' are shown in Figure 3.5. The water layer along profile B-B' is about 600 m thick; the sediment layer becomes thinner (50 m at the cross-point). Along profile C-C' the water thickness decreases to 250 m, while sediment thickness remains about 50 m. The inversion for profile D-D' (along the lake, Figure 3.6) shows a significant and sharp rise of the lake bottom in the northern part dividing the lake into two sub-basins. The water thickness over this rise is only about 100 m. Since there

a.



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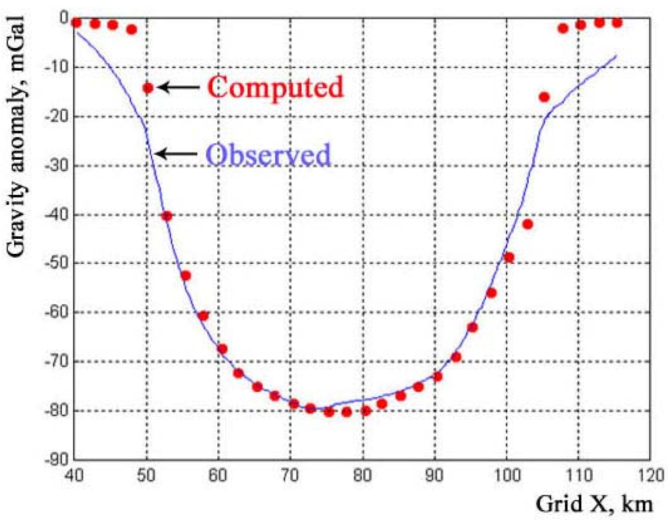

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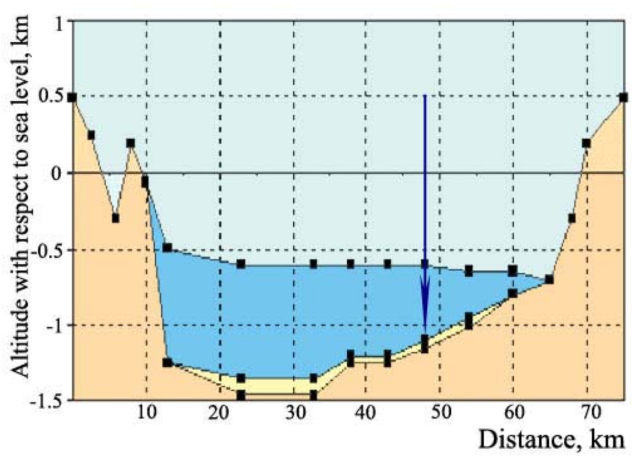


Figure 3.4 The results of 2D inversion for profile A-A’, Lake Vostok and its comparison with the seismic profile:

a. A model for inversion consists of the ice/water (950 kg/m^3, light and dark blue) and sedimentary (1850 kg/m^3, yellow) layers overlying the host rock of density 2550 kg/m^3; the arrow shows the intersection point with the seismic profile shown in section c of this figure;
b. Measured (solid line) and calculated (dots) gravity anomaly;
c. The seismic profile across the lake (for the location see Figure 3.2).

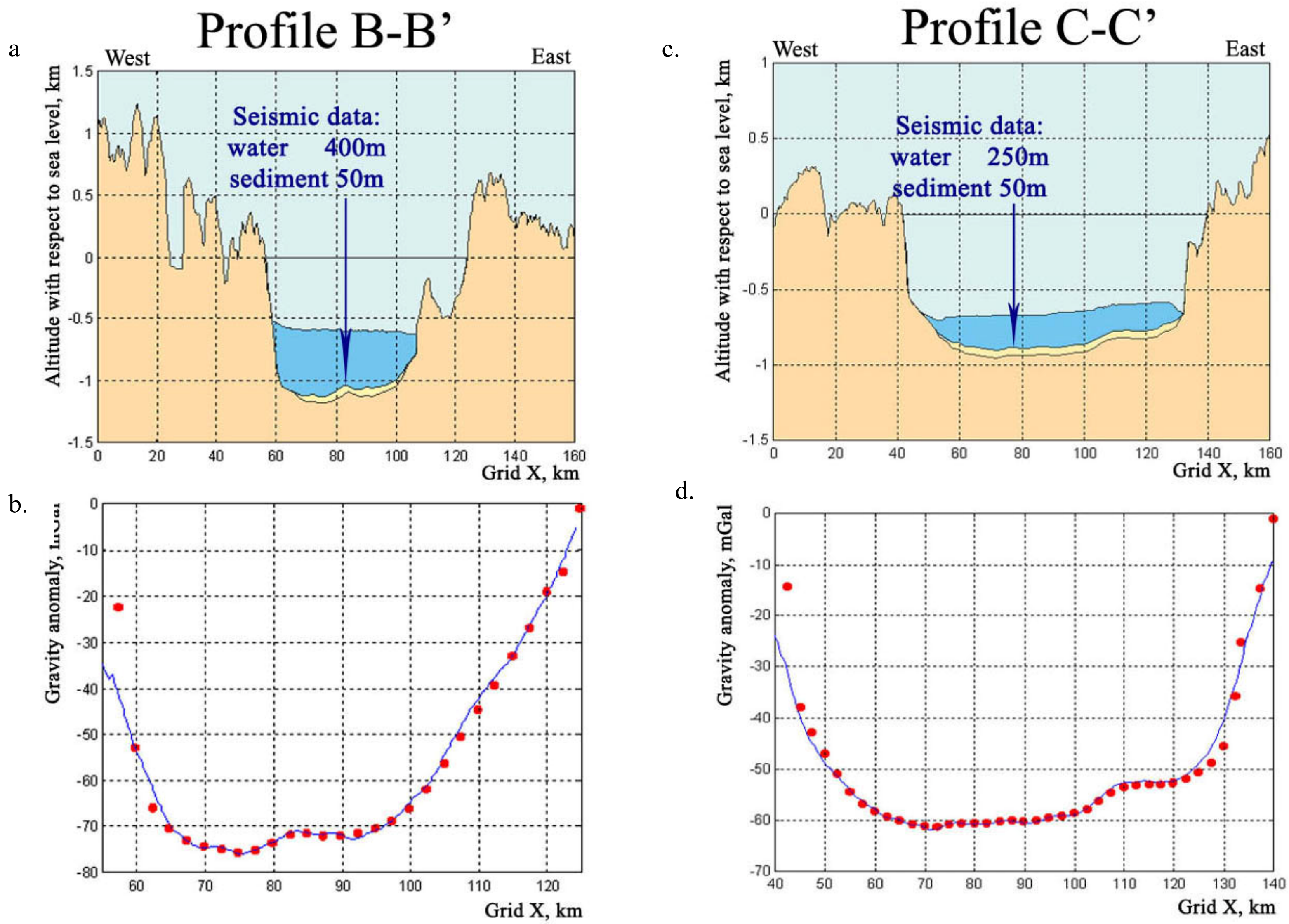


Figure 3.5 The results of 2D inversion for profiles B-B' (a., b.) and C-C' (c., d.) over Lake Vostok (for the location see Figure 3.2); see the explanation in Figure 3.4 for the details.

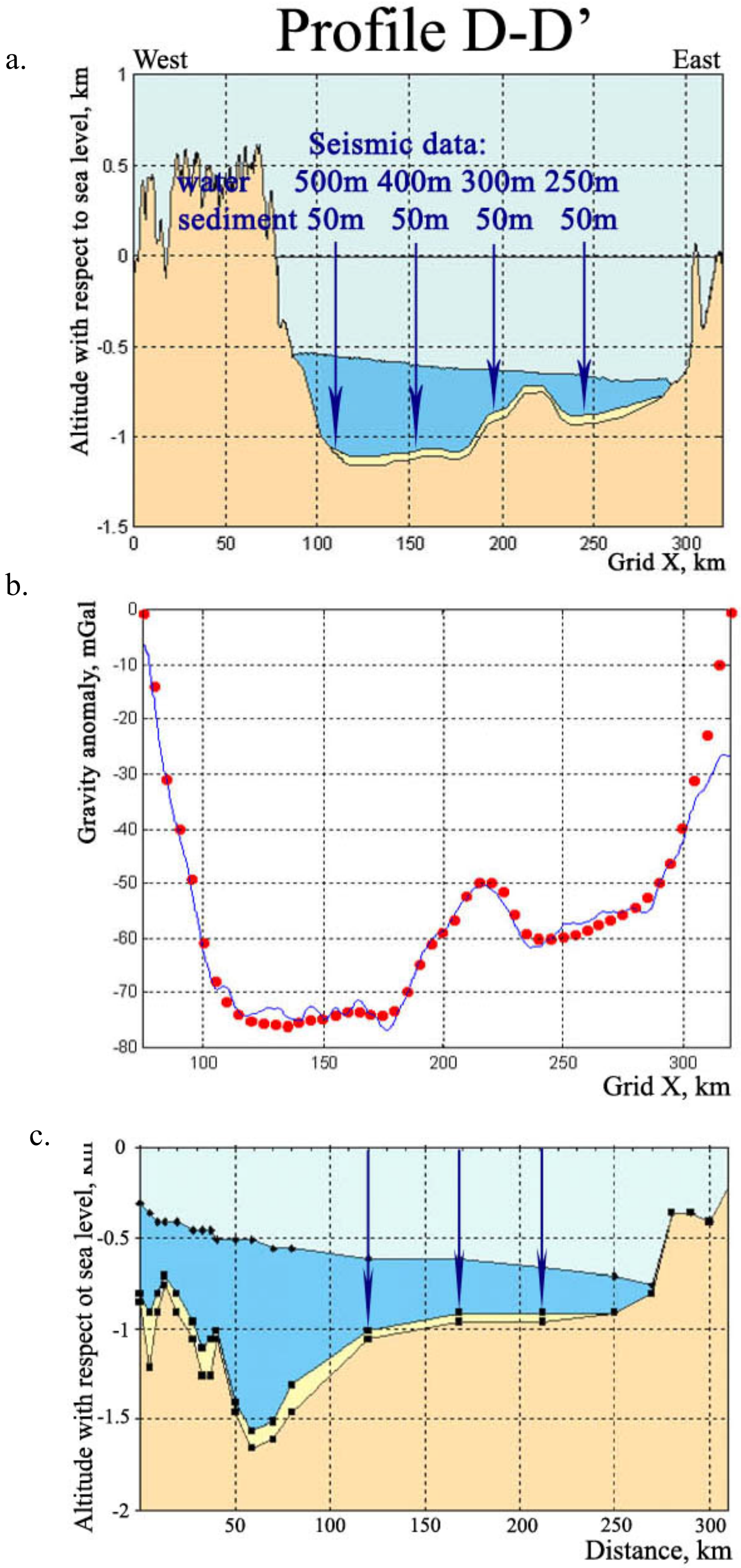


Figure 3.6 The results of 2D inversion for profile D-D’, Lake Vostok (a., b) and its comparison with the seismic profile along the lake (c.). For the location see Figure 3.2; see the explanation in Figure 3.4 for the details.

exist only a few seismic soundings in the northern part of the lake (40 km between shots, Figure 3.6.c), this feature in the lake's bottom topography was not recognized in previous seismic surveys. The largest difference between water thickness derived from gravity and that from seismics at coincident points is 100 m.

3.5 The results over Lake Vostok: 3D case

The 3D inversion of the airborne gravity data was performed in 2004 and presented at the First Scientific Committee on Antarctic Research (SCAR) Open Science Conference in Bremen, Germany, in July 2004 (Filina et al., 2004). By that time 45 seismic data points became available (Item CEP 4c, 2002; red dots in Figure 3.8). According to the reinterpreted seismic data (Item CEP 4c, 2002), the thickness of sedimentary layer in Lake Vostok varied from 40 to 100 m. The sedimentary layer thickness, constructed for the whole lake area based on seismic points, was fixed during 3D inversion because its gravity effect is significantly smaller than that of the water layer.

Before the inversion the regional trend (Figure 3.3) was removed from the reduced free-air anomaly. The resultant residual anomaly is shown in Figure 3.7. The preliminary 2D inversion showed that the best agreement between gravity-derived water thickness and seismic data was achieved for a host rock density of 2550 kg/m^3. 3D inversion was performed for the host rock densities of 2550 kg/m^3, 2600 kg/m^3 and 2670 kg/m^3. The maximum difference in water thickness derived for the host rock densities of 2550 kg/m^3 and 2670 kg/m^3 is 180 m.

The result of 3D modeling is shown in Figure 3.8. The bathymetry model inverted

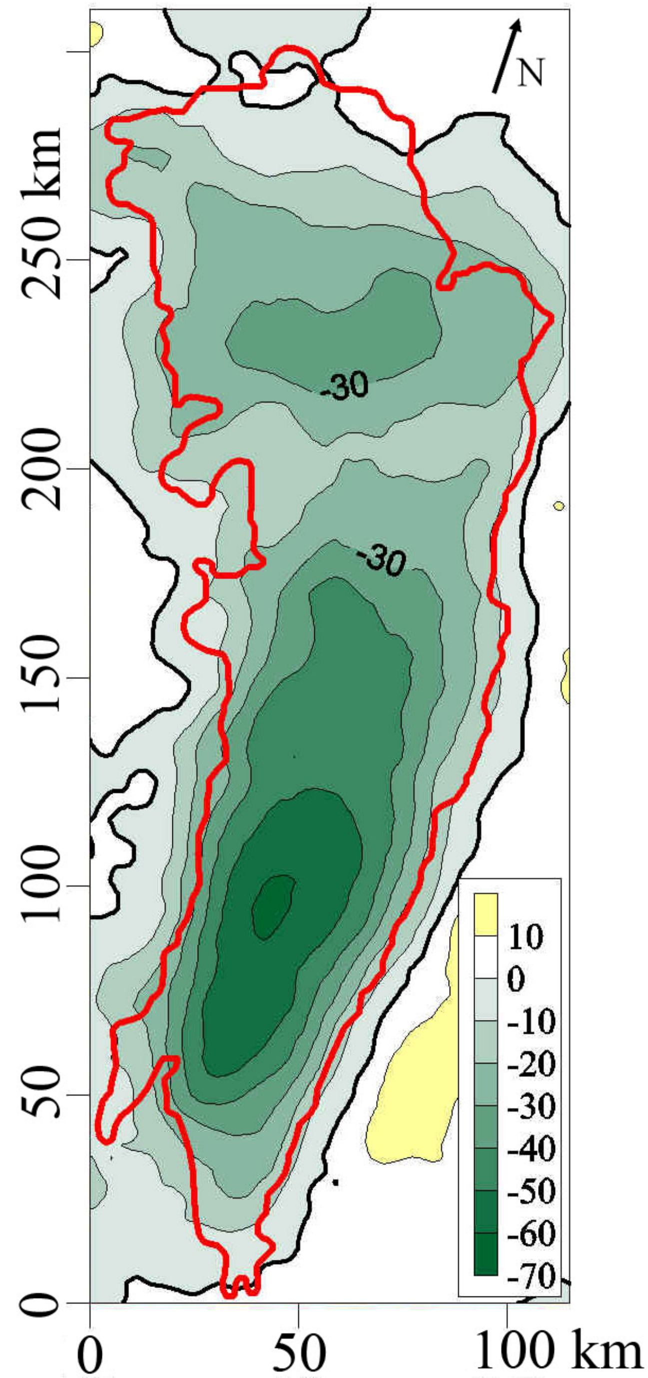


Figure 3.7 The residual gravity anomaly over Lake Vostok; contour interval is 10 mGal. The thick black line corresponds to zero mGal; red line shows the lake's coastline from radar data.

a.

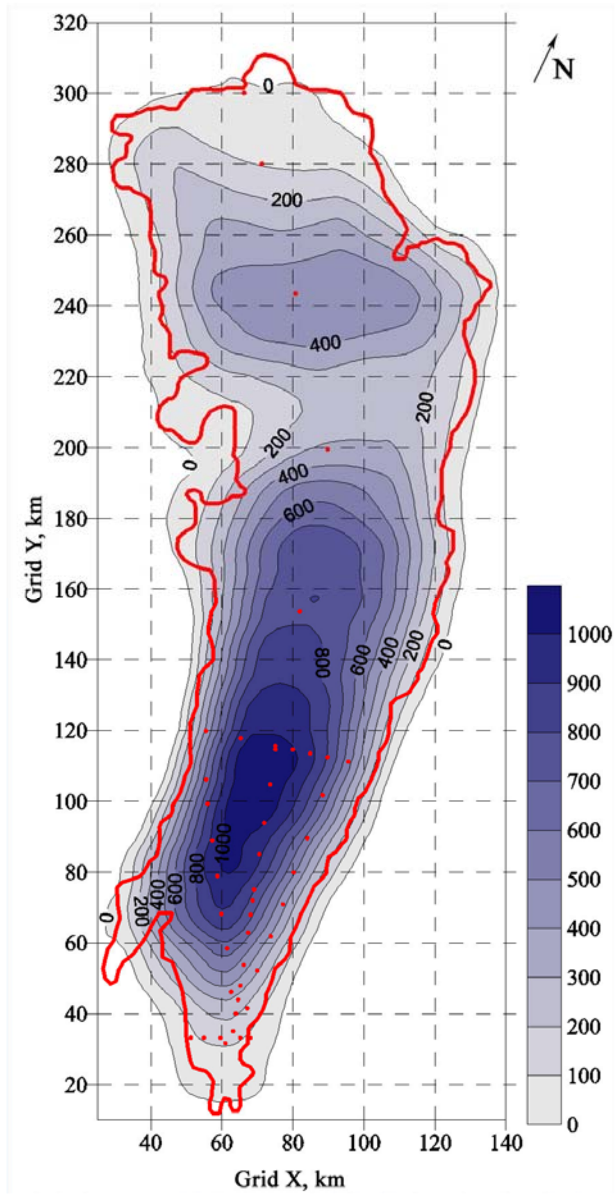
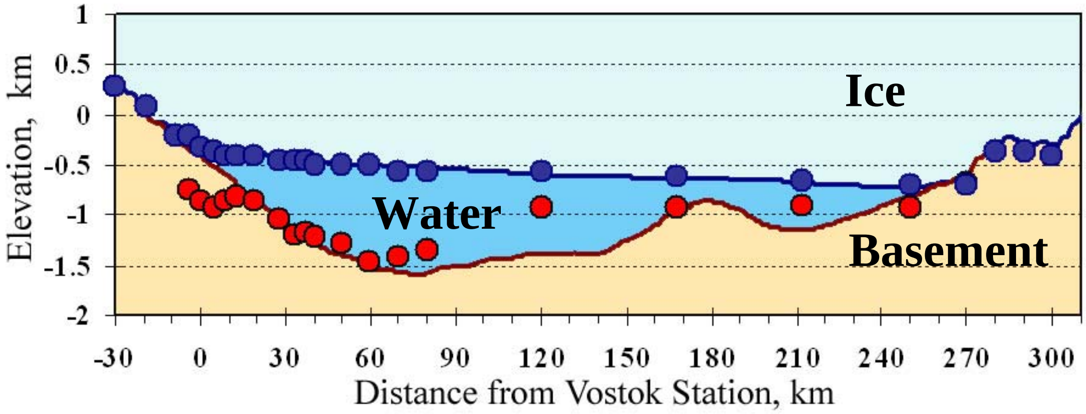


Figure 3.8 The results of 3D inversion of airborne gravity data for Lake Vostok derived for the host rock density of 2550 kg/m^3 (from Filina et al., 2004)

a. Water thickness; contour interval is 100 m. Red line outlines the coast line of the lake from radar data; red dots show the location of seismic soundings used to constrain the model;

b.

Profile along the lake



Profile across the lake

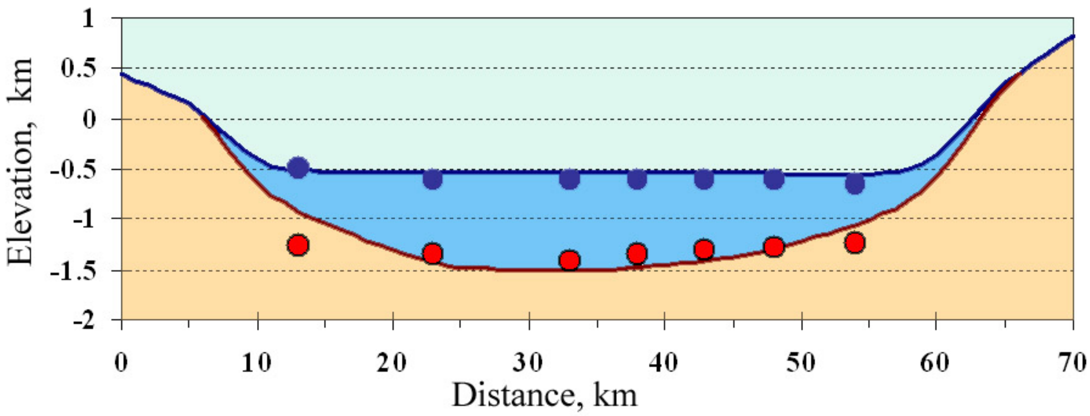


Figure 3.8. (continued)

b. The difference in lake bathymetry derived by gravity inversion for host rock density of 2550 kg/m^3 (solid lines) and seismic data along profiles 1-1' and KM from Item CEP 4c (2002). The blue and red dots show the bottom of the ice and water from seismic data respectively. The sedimentary layer, which is 40 – 100 m thick (Item CEP 4c, 2002) is not shown at the bottom of the lake to avoid confusion. The locations of profiles are shown in Figures 2.3 and 3.2.

for the host rock density of 2550 kg/m^3 was compared with seismic data in 45 locations over the lake, showing the standard deviation of 200 m.

In general, the inversion shows that the bottom of the lake has a sharp rise in the northern part, dividing the lake into two sub-basins. The water thickness in the southern basin exceeds 1000 m, while the northern basin appears to be shallower – up to 450 m according to 3D gravity modeling. This value disagrees with the water thickness derived from seismic soundings (250 m in the northern basin).

3.6 Discussion

The 2D and 3D inversions showed two major results:

(1) The best fit between gravity and seismic data was achieved for the host rock density of 2550 kg/m^3, suggesting that the lake is hosted by sedimentary rocks. This conclusion is consistent with both proposed geological models for Lake Vostok (Studinger et al., 2003b; Leitchenkov et al., 2003 and 2005). In spite of the fact that those models suggest different origins of Lake Vostok, they both imply the presence of sedimentary basin beneath the lake filled with sedimentary rock of density of 2500 kg/m^3 (Studinger et al., 2003b). The presence of sedimentary rocks in the Lake Vostok area was shown later from analysis of the inclusions found in the samples from the 5G-1 borehole drilled at Vostok Station (Leitchenkov et al., 2007). Those rock grains are believed to be scoured by the ice sheet from the area up-flow (west) of the lake and have been carried by the moving ice over the lake. Analysis of the inclusions showed that they are grains of siltstone, proving the presence of sedimentary rocks in the area adjacent to Lake Vostok.

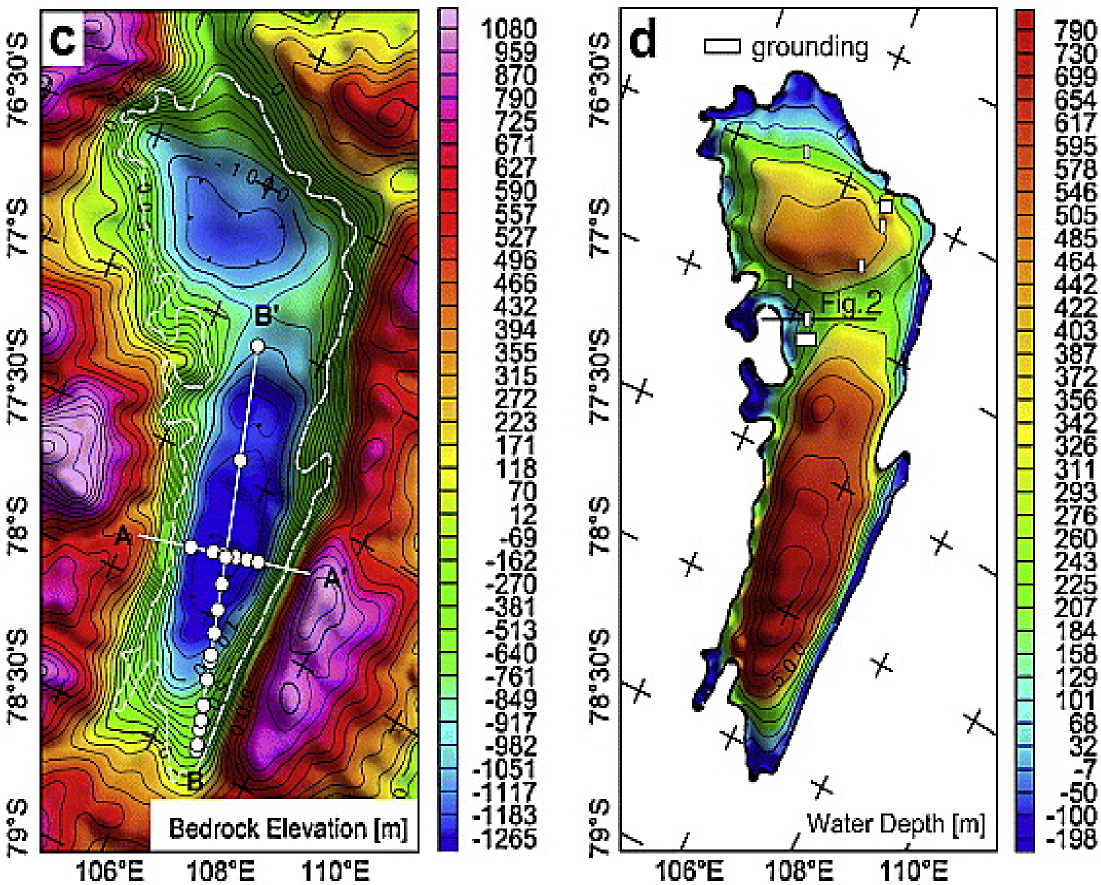
(2) The inversions also showed that the lake's bottom has a rise in the northern part, which divides the lake in two sub-basins: a large and deep basin in the southern part and

a relatively small and shallow one in the north. This rise appears to be less than 40 km wide. The water thickness above this feature does not exceed 200 m. Since the seismic data available to date were collected with the spatial interval of 40 km between the data points, this rise in the lake's bottom was missed in seismic data.

The latter conclusion was later supported by Studinger et al. (2004), who performed 3D modeling of the same aerogravity data to estimate water depth in Lake Vostok (Figure 3.9). Since the sedimentary layer was believed to be thin, it was ignored in Studinger et al.'s (2004) modeling. Their model shows a maximal water thickness in the lake of 800 m in the southern basin and about 450 m in the northern basin. Their comparison with seismic data at 19 points (RMS of 250 m, Figure 3.9.b) shows better agreement than the model of Roy at al. (2005) but worse than my 3D results. The Studinger et al.'s (2004) model was developed for a density of the host rock of 2670 kg/m^3. A regional trend of second order was calculated based on "the misfit between the regional bedrock topography inverted from gravity and the bedrock topography from radar data" (Studinger et al., 2004).

There is a discrepancy between the results of my presented 2D and 3D modeling in regards to water thickness in the northern basin. The 2D model shows the water thickness of ~250 m, while 3D modeling suggests the presence of more than 400 m of water in the northern basin, consistent with Studinger et al., 2004. This discrepancy in water thickness in the northern part of the lake, observed in seismic method and calculated from gravity, is believed to be due to uncertainty in the 2D regional trend that is responsible for the deep geological structures. The trends found for 2D profiles are less reliable than the 3D regional trend. The latter is more constrained since it includes information from the entire survey area, and consequently is more certain. That is why

a.



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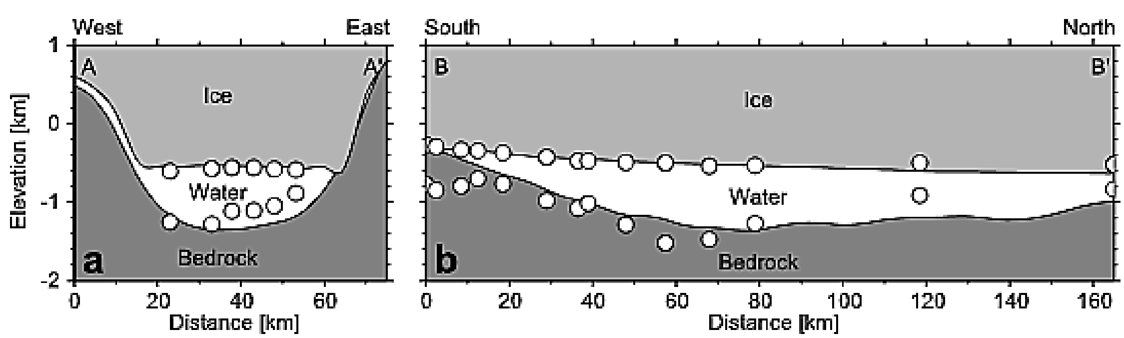


Figure 3.9 3D bathymetry model of Lake Vostok developed by Studinger et al., 2004:

a. The water depth and water thickness in Lake Vostok as a result of 3D inversion of airborne gravity data for the density of the host rock of 2670 kg/m^3.
b. The comparison with seismic data in 19 points shows RMS of 250 m.

the results of the 3D inversion have more credibility, although they disagree with available seismic data that suggest water thickness in the northern part of Lake Vostok is 250 m. I explain this discrepancy later by showing that an inaccurate sediment distribution was incorporated into the model (Chapters 5 and 6).

3.7 Summary

2D and 3D modeling of airborne gravity data was performed for subglacial Lake Vostok, East Antarctica using different values of density contrasts between ice/water and the surrounding rock. Sparse seismic data available to date were used to constrain the model. The results show that the best agreement between seismic and gravity models was achieved for density of the host rock of 2550 kg/m^3, inferring that the lake is hosted by sedimentary rocks. The modeling shows a topographic rise in the northern part of the lake, which divides Lake Vostok into two sub-basins: a large and deep basin in the southern part and a relatively small and shallow one in the north. This rise appears to be less then 40 km wide. The water thickness above this feature does not exceed 200 m. Since the seismic data available to date were collected with the spatial interval of 40 km between the data points, this feature in the lake's bottom topography was not recognized in previous seismic surveys.

Chapter 4: Bathymetry of subglacial Lake Concordia, East Antarctica

4.1 Introduction and objectives for the study

Lake Concordia is currently the eighth largest subglacial lake known to date in Antarctica (Figure 1.1). This lake has been known since 1999-2000 when the University of Texas Institute for Geophysics (UTIG) performed an airborne geophysical survey in the Dome C area, revealing the lake (Figure 4.1). Lake Concordia is significantly smaller and much less studied than Lake Vostok.

As in Lake Vostok, the ice thickness over Lake Concordia is not constant (Figure 4.2). The southern portion of the lake is covered with thicker ice (up to 4100 m), while the ice thickness decreases to 4000 m in the northern part of the lake (Figure 4.2).

Lake Concordia is believed to be associated with normal faulting (Tabacco et al., 2006) based on the modeling of the bedrock morphology from the radar sounding data. The initial estimation of the water depth in Lake Concordia was performed by Tikku et al. (2002) based on analysis of gravity data, reporting that water depth in Lake Concordia is less than 1000 m. Another estimation was made based on the interpolation of the steep slopes marking the coastline of the lake (Tabacco et al., 2004), suggesting that the minimal water thickness in Lake Concordia should be 200 m. A revised analysis of airborne radar data (Tikku et al., 2005) suggested that the lake is 200 -300 m deep with a maximal lake volume of 200 ± 40 km^3. The analysis of Tikku et al. (2005) also suggests that melting at the base of the ice takes place in the southern part of the lake, while freezing occurs at the north. To date, there are no seismic soundings performed over Lake Concordia.

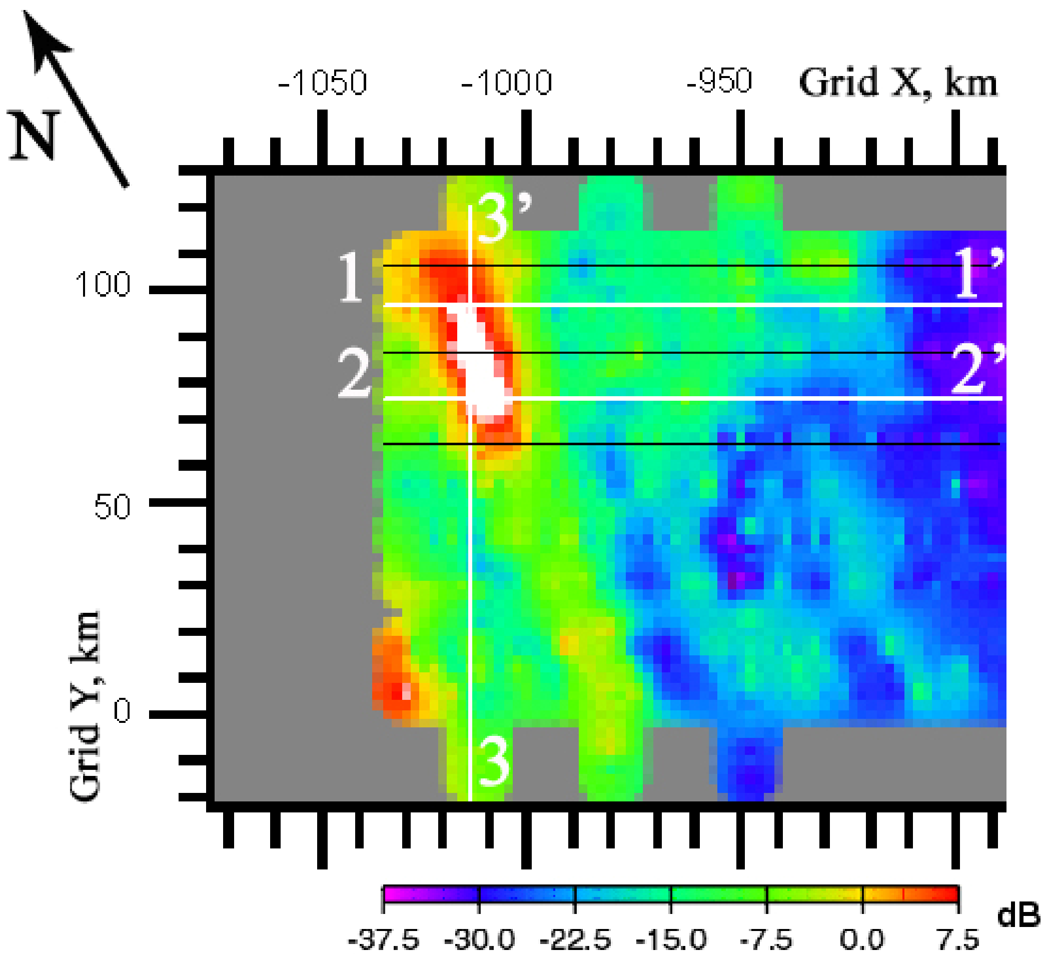


Figure 4.1 The radar sounding bed echo strength map over Lake Concordia (from Carter et al., 2007). The region of bright echoes is believed to be a lake. The black lines show the location of profiles that lack gravity data and can not be used in the modeling. The white lines show the profiles used for the inversion (see the results in Figure 4.3).

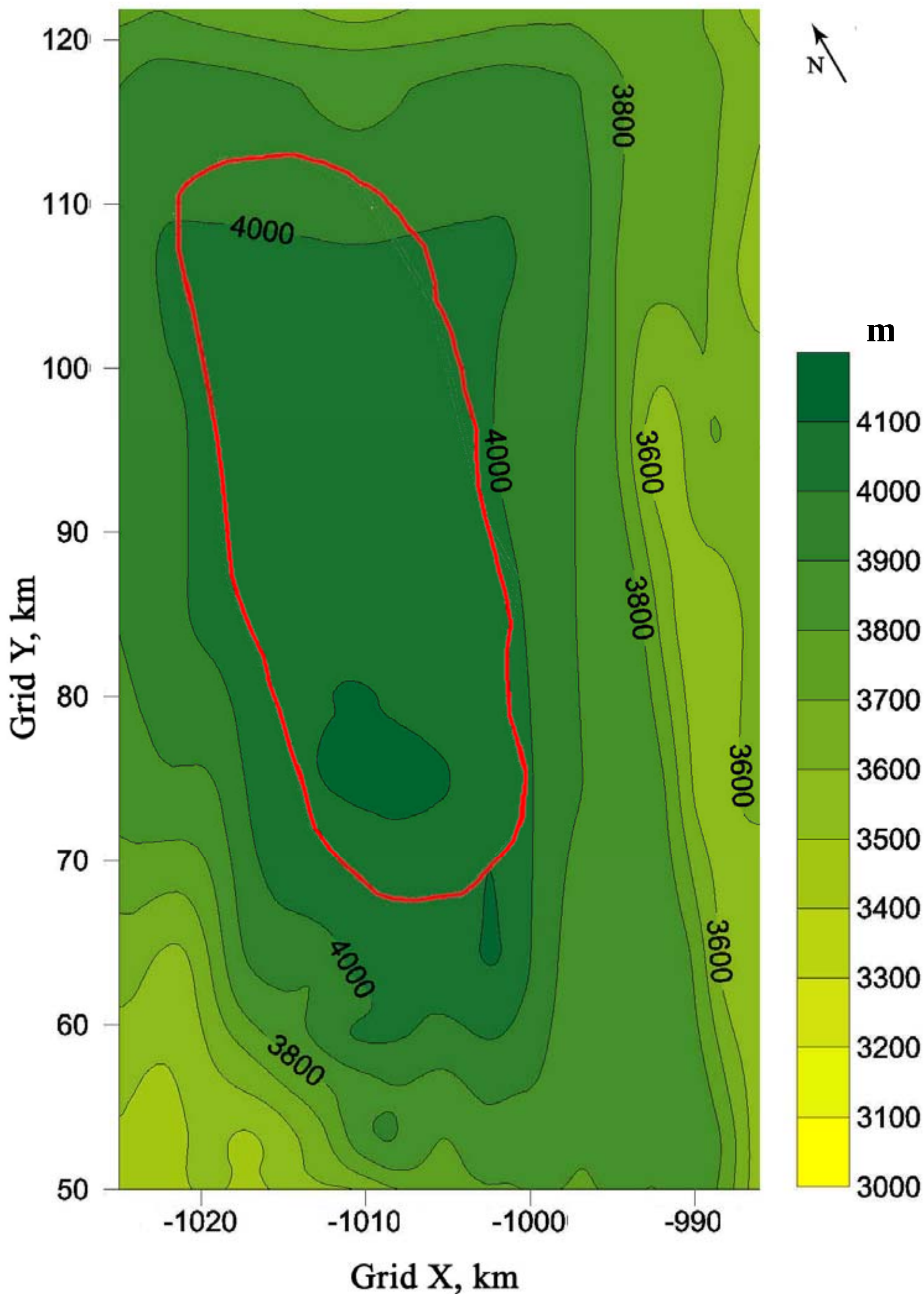


Figure 4.2 The thickness of ice over subglacial Lake Concordia, showing that the ice in the southern portion of the lake is ~100 m thicker than the ice over the northern part of the lake. Contour interval is 100 m.

The major objective for the study was to estimate the water thickness and any sediment distribution in Lake Concordia via analysis of airborne gravity data. Since there is no seismic constraint for Lake Concordia, such analysis should be done for the range of possible host rock densities.

4.2 The data used in the study

The airborne survey over Lake Concordia, East Antarctica, was performed by UTIG during the 1999 – 2000 austral summer. Spacing between survey lines was 10 km. A radar sounding bed-echo-strength map (Carter et al., 2007) is shown in Figure 4.1; the dark region in the northern part, which is about 50 km long and 20 km wide, is assumed to be the lake. The estimated surface area of Lake Concordia based on the coastline from the above map is 630 km^2, which is ~ 20% smaller that the estimate of Tikku et al. (2005).

The region of Lake Concordia is sampled with 6 profiles (Figure 4.1). The algorithm developed by T. Richter of UTIG (Appendix 3) was used to reduce the airborne gravity data over subglacial Lake Concordia. The gravity reduction algorithm requires cutting off the end and the beginning of profiles (typically at half filter width; in this case 7.5 km, due to the moving average filter width was 15 km). Also, the aircraft direction of motion along the profile is important. To start a profile an aircraft makes sharp turn, and the gravity meter needs some time to be stabilized. That is why some part of profile that starts over the survey edge is subject to large accelerations and has to be removed. In the case of Lake Concordia three of the six profiles that start over the lake have to be muted due to the reduction algorithm (black lines in Figure 4.1). This muting, unfortunately, covers most of the lake portion of those three profiles.

Since Lake Concordia is sampled by three remaining gravity profiles only (white lines in Figure 4.1), the data precision cannot be adequately evaluated based on the analysis of the crossover points. The data for a repeated line outside of the lake area in the same survey were used to estimate the accuracy of the reduction (see Appendix 3). The RMS of the difference of free-air anomaly for two profiles along the repeated line is 1.6 mGal.

4.3 The results of 2D and 3D inversion of airborne gravity data over Lake Concordia

The fact that the lake is located at the very edge of the survey creates an uncertainty in finding the regional trend. Since there is no data to the north of the lake, the regional trend was evaluated south of the lake and then extrapolated over the lake for both 2D and 3D cases.

The 2D and 3D inversions of the gravity data were performed using several fixed values of the host rock density (from 2550 to 3000 kg/m^3 between ice/water and host rock). Figure 4.3 shows the results of 2D modeling for three profiles over Lake Concordia (see the location in Figure 4.1) using a density of 2550 kg/m^3, which gives the best agreement with seismic results for Lake Vostok (Chapter 3). The differences in water thickness at cross-over points of inverted profiles for all density contrasts are within 50 m.

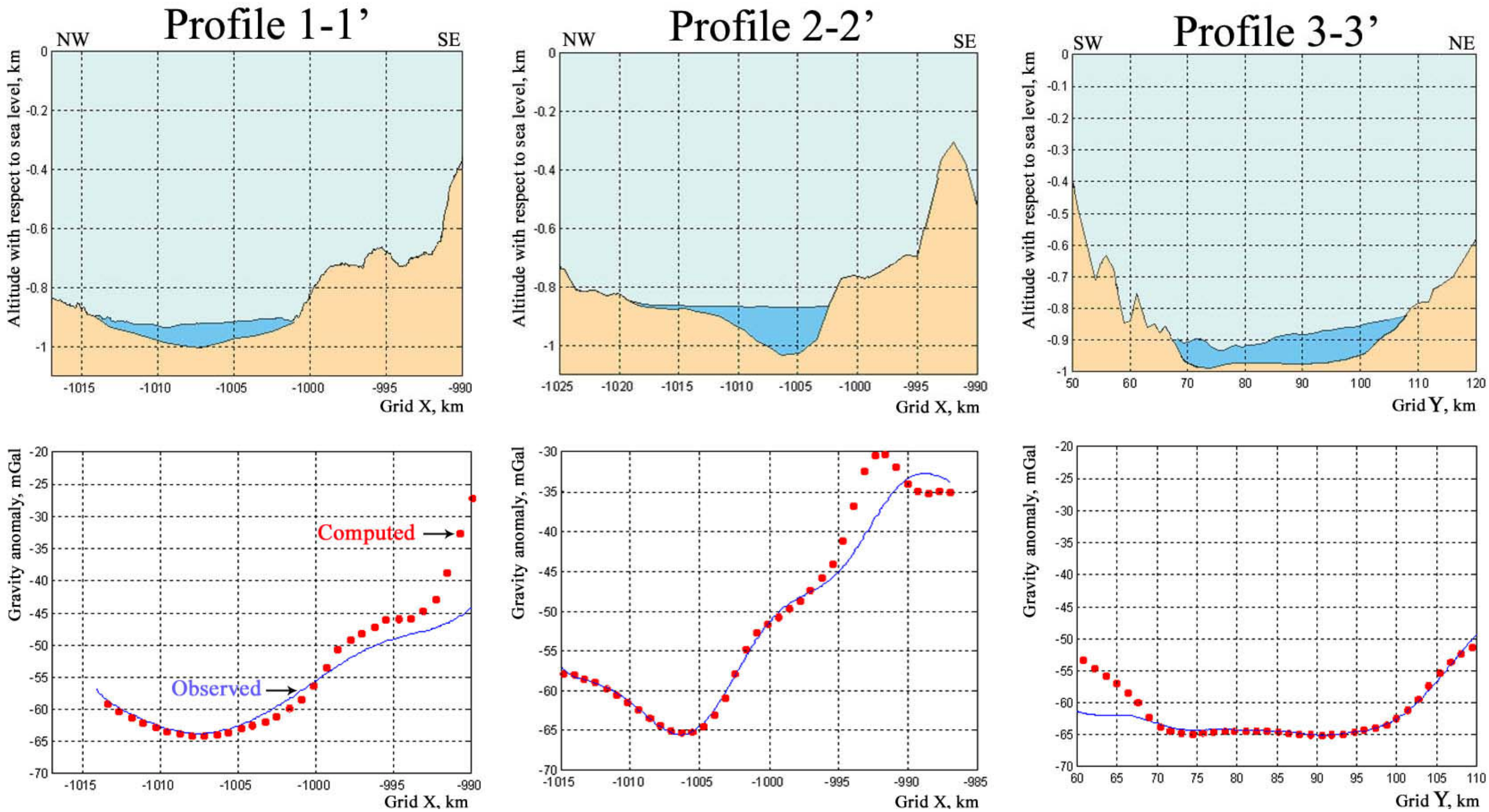


Figure 4.3 The results of 2D inversion of airborne gravity data for Lake Concordia (the density of the host rock is 2550 kg/m^3, which gave the best agreement with seismic data for Lake Vostok). The top figures show the model for inversion composed of the ice (920 kg/m^3) and water (1000 kg/m^3) layers overlying the host rock. The bottom figures show the fit between the observed gravity anomaly (solid) and the calculated one (dots).

For all density contrasts used, the water thickness in Lake Concordia does not exceed 200 m. If the density of 2670 kg/m^3 for the host rock was used (as in Tikku et al., 2005), the inversion suggests the maximal water thickness in Lake Concordia of ~125 m (Figure 4.4). In the assumption that Lake Concordia is hosted by igneous rocks with density of 3000 kg/m^3 or higher, the lake disappears, because the modeling shows negative water thickness. The modeling suggests that the lake volume is 70 km^3 using the assumption that the lake is hosted by sedimentary rocks. This is three times less than the volume estimated by Tikku et al., (2005). Since Lake Concordia is relatively shallow, a sedimentary layer cannot be resolved and it was neglected.

The results of 2D modeling of gravity data over Lake Concordia were presented at the IX International Symposium on the Antarctic Earth Sciences in Potsdam, Germany in September 2003 (Filina et al. 2006a), and at the AGU Fall meeting in 2003 (Filina et al., 2003). The follow-up 3D bathymetry model was presented in the First Scientific Committee on Antarctic Research (SCAR) Open Science Conference in Bremen, Germany, in July 2004 (Filina et al., 2004).

Overall, the inversion suggests that Lake Concordia's basin has a gently deepening western border and relatively steep eastern one with the maximum water depth in the north-eastern part of the lake. The freezing of the lake's water onto the ice bottom occurs at the northern part of the lake (Tikku et al., 2005), where the thinner ice is recorded by radar sounding and the deepest water thickness is estimated from the gravity modeling. This pattern is very similar to the one observed in Lake Vostok, where freezing coincides with the deeper southern part of the lake that is covered with thinner ice. The melting in Lake Concordia (Tikku et al., 2005) coincides with the shallow southern portion of the lake, covered with the thicker ice. This, again, is similar to the melting

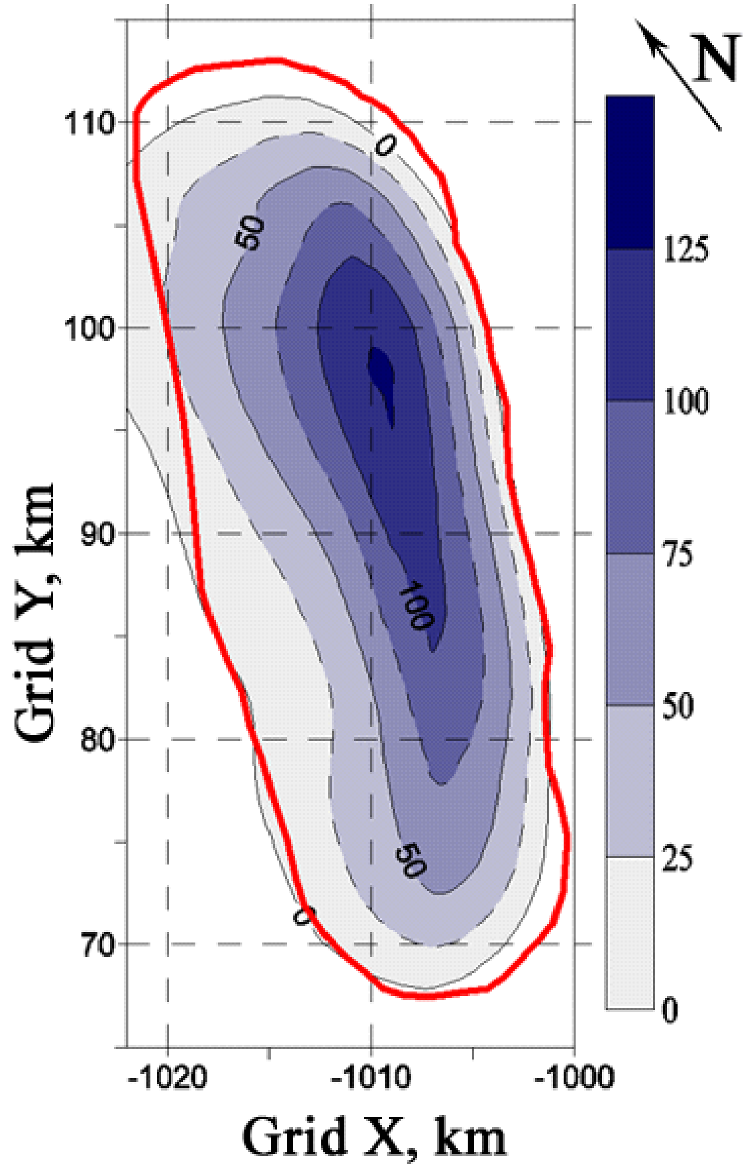


Figure 4.4 The results of 3D modeling over Lake Concordia for the host rock density of 2670 kg/m^3 (from Filina et al., 2004). Contour interval is 25 m. The red line shows the coastline from radar data.

pattern observed in Lake Vostok, where melting occurs in the shallower northern basin covered by the thicker ice.

To date more than 145 subglacial lakes are identified beneath the Antarctic ice sheet (Siegert et al., 2005; Bell et al., 2006 and 2007). Lakes Vostok and Concordia are the only two of the large subglacial lakes that have been covered by airborne geophysical surveys. The availability of these datasets allows to estimate surface area, water volume and water distribution in these lakes, as well as to analyze internal processes, such as melting and freezing, that operate within these lakes. In contrast, most of the other lakes are identified based on single radar profiles (Siegert et al., 2005), or the analysis of satellite data (Bell et al., 2006 and 2007). The comparison of the observed similarities in Lake Vostok and Concordia allows us to infer that a similar pattern should be expected in other subglacial lakes. Based on the comparison of the data over Lake Vostok and Lake Concordia the following three facts may be expected to be valid for other subglacial lakes:

(1) The ice thickness over the lake is not uniform. The gradient of the ice-water interface should be ~ 10 times that of the ice sheet surface, and in the opposite direction (Siegert, 2005).

(2) The area with the thicker ice is subject to melting of the ice sheet at the ice-water contact. This area is coincident with the shallower lake's part.

(3) The deeper part of the lake lies under the thinner ice, which is dominated by freezing of the lake's water at the bottom of the ice.

Chapter 5: Presence of unconsolidated sediments at the bottom of Lake Vostok from seismic data

5.1 Motivation and objectives for the study.

Seismic experiments at Vostok Station have been conducted since 1995 by the Polar Marine Geological Research Expedition (Saint Petersburg, Russia) in collaboration with the Russian Antarctic Expedition (Saint-Petersburg, Russia). Since then, more than a hundred seismic soundings have been acquired, mostly located in the southern part of the lake (Figure 2.3). The primary objectives of the initial seismic experiments were to prove that there is a layer of water beneath the ice and to measure the depth of the lake and the thickness of any unconsolidated sediments at the bottom of the lake. The presence of unconsolidated sediments at the bottom of Lake Vostok has been a subject for debate for the last several years when all acquired seismic data were reinterpreted (A. Popkov, 2005 – personal communication; Masolov et al., 2006).

To date, six seismic profiles are published (Masolov et al., 1999 and 2006; Item CEP 4c, 2002; Figure 2.3). Three of those profiles are oriented along the lake, while three others traverse the lake with the densest data coverage in the southern portion in the vicinity of Vostok Station. Overall, the seismic data suggest that the southern part of the lake is deeper, with the maximal water thickness up to 1200 m located ~50 km to the northwest of Vostok Station (Masolov et al., 2006; Item CEP 4c, 2002; point 9S47 located at ~40 km along profile S47 shown in Figure 2.5). The water thickness decreases up to 250 m in the northern part of the lake (Profile 1-1' in Figure 2.4.b). The seismic data suggest that there is a relatively small (about 5 km) and deep (up to 680 m) basin floored by sediments at the southern part of the lake in the vicinity of Vostok Station (Figure 2.4.a; Masolov et al., 1999; Item CEP 4c, 2002).

Gravity modeling (Chapter 3; Filina et al., 2004, 2006a and 2007b; Studinger et al., 2004) shows a ~40 km wide topographic rise in the northern part of the lake that divides Lake Vostok into two sub-basins: a large and deep basin in the southern part and a relatively small and shallow one in the north. Since the spacing between seismic soundings in the northern part of the lake is 40 km, this feature in the lake bottom topography was missed in seismic profiling along the lake.

Earlier publication of seismic results (Masolov, 1999; Figure 2.4.a) reported that "the lake is floored by sediments forming a layer at least several hundreds of meters thickness…The total sediment thickness varies from tens of meters to 350 m". The seismic velocity in sediments was assumed to be 2650 m/sec.

Later publication (Item CEP 4c, 2002; Figure 2.4.b) concludes that "the bottom surface appears to be represented by modern sedimentary features bedding on the acoustic basement. The thickness of sediments is 40 - 110 m. In the flank areas of the lake, the bottom is represented by acoustic basement rocks". In that publication the velocity in sediments was assumed to be 2500 m/s. However, the most recent publication (Masolov at al., 2006) suggests that the lake's water overlies the acoustic basement (Figure 2.5), implying that there is no sedimentary layer at the bottom of Lake Vostok.

The reason for this discrepancy is that the recorded seismograms (Figures 5.3, 5.5-5.7) show at least two relatively closely spaced reflections after the ice-water echo, which hereafter will be called secondary bottom reflections. The latest interpretation suggests that the secondary bottom reflections in these seismic records, which used to be interpreted as boundaries of a sedimentary layer, are just side reflections due to the lake bottom's roughness (A. Popkov, 2005 – personal communication). Thus, understanding the nature of these secondary bottom reflections should reveal the presence or absence of unconsolidated sediments in Lake Vostok. The objective for this study is to test several hypotheses for the origin of these events in the seismograms to prove or disprove the presence of the unconsolidated sediments at the bottom of Lake Vostok, which is tightly connected to the lake's history. Thick sedimentary layer may reveal whether or not the lake existed before the current glaciation, which is believed to last about 30 Myr (Duxbury et al., 2001). Different sedimentation mechanisms for Lake Vostok and their estimated rates will be addressed in Section 6.4.

5.2 Available data and method

Seismic data in four different locations over the lake were used in this study (Figure 5.1). The locations for these points were chosen to be in the vicinity of Vostok Station, where the lake bottom topography is rough, as well as in the middle and the northern part of the lake, where the lake bottom is relatively smooth. However, only one point out of four analyzed was located in the northern basin.

The data used were recorded by a 600 m long, 24 channel linear array with a 25 m interval between geophones. The distance from the shot points to the first geophone was in the range of 3.5 – 4.0 km. An explosive cord was used as the source of acoustic waves (Masolov et al, 1999). The recorded data have a significant groundroll masking the reflections. To suppress this, FK filtering was performed before interpreting the data.

The first strong reflection observed in the seismograms corresponds to the ice-water interface (see Figure 5.3, 5.5 - 5.7). A polarity reversal of the seismic wave occurs on this boundary, so during the traveltime picking each trough was digitized for this event. For all following bottom reflections the peaks were digitized.

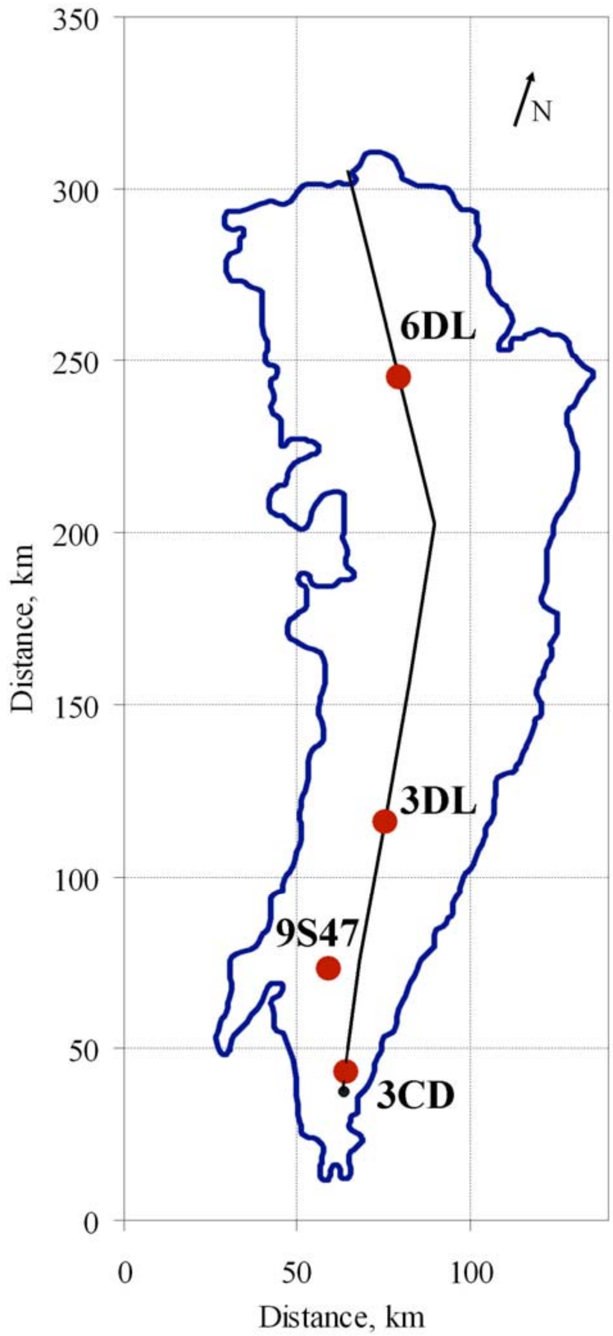


Figure 5.1 Location of the four seismograms analyzed in this study. Blue line is the lake's coastline from radar sounding; black line marks the location of seismic profile along the lake shown in Figure 5.8.

Ray tracing through a set of layers parameterized by fixed velocity, thickness and slope was used to solve the forward problem of determining the traveltime at each receiver. The ray was initiated at the source point and propagated through the assumed set of layers, then reflected (or refracted) based on Snell's law and traced up to the receiver point. A traveltime inversion was later performed by a conjugate gradient method (Tarantola, 1987) for different sets of model parameters depending on the hypothesis tested.

'A priori' information incorporated in all models included the flat ice/water boundary ($\ll$1 deg, Studinger et al., 2003a), and the average velocity of the seismic waves in the ice (including the snow-firn layer), which was measured at Vostok station (Masolov et al., 2006) to be 3810±20 m/s. The seismic velocity in the water was chosen to be 1490 m/s as in Masolov et al., 2006.

5.3 Tested hypotheses

Three hypotheses were proposed for the origin of the secondary bottom reflections (Figure 5.2). The first hypothesis assumes that there is no sedimentary layer at the bottom of the lake; it implies that the secondary reflection is due to non-flat water/basement boundary along the source-receivers line (SRL) (2D case, Figure 5.2.a).

Since the acoustic velocities in ice and water are known, the water thickness and the slope of the lake bottom are model parameters for each secondary bottom reflection. As a result of the inversion, the position of the water/basement boundary was obtained for each bottom reflection, and their compatibility with each other was a criterion for accepting this hypothesis.

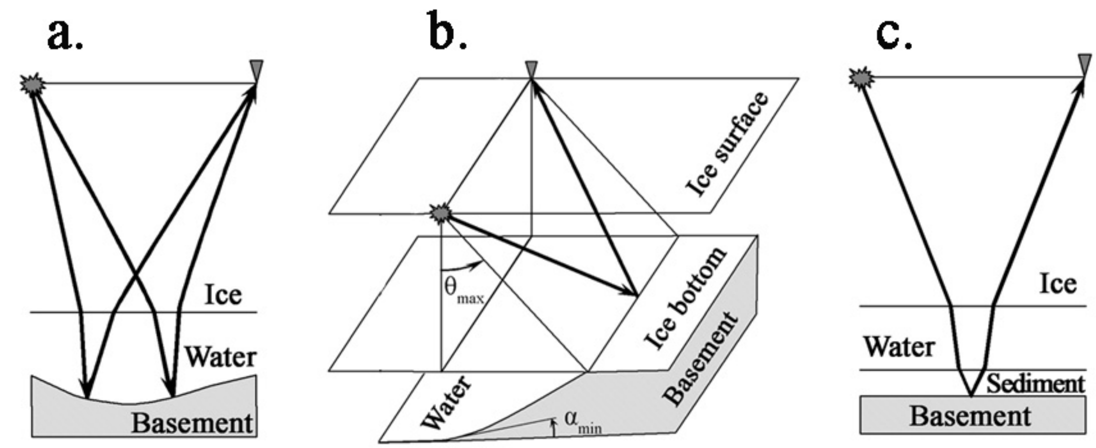


Figure 5.2 Three hypotheses for the origin of the secondary bottom reflections in the seismic records over Lake Vostok. A star and an inverted triangle indicate source and receiver respectively.

a. Non-flat lake bottom (2D case);
b. A side echo (3D case)
c. A layer of unconsolidated sediments at the bottom of the lake.

The second hypothesis also assumes the absence of a sedimentary layer. In this case the secondary bottom reflections are assumed to be side echoes from a lake bottom slope adjacent and striking parallel to the SRL (see Figure 5.2.b). To have a reflection from this topographic plane, the ray should travel in the inclined plane. The maximal inclination of this propagation plane can be estimated based on the traveltime of each reflection, seismic velocity in the ice, and known ice thickness. If the propagation plane is inclined with the angle θ_{max}, the ray travels through the ice layer only, since it does not have time to propagate through the water. The next step was to divide this calculated angle, θ_{max}, into a number of intervals, and to calculate, for each inclination angle, the water depth corresponding to each of the water/basement secondary bottom reflections. The set of possible locations obtained then allows to estimate the minimal sloping angle

α_{min} of the inclined plane striking parallel to the SRL.

The last hypothesis to test is the presence of a sedimentary layer at the bottom of the lake (Figure 5.2.c). In this case, horizontal layers were assumed while the seismic velocity in the sedimentary layer and its thickness were the model parameters.

5.4 The results

5.4.1 Seismogram 3CD

The most southern point – 3CD (see Figure 5.1) – is located ~5 km north of the Vostok Station. The first receiver was placed at a distance of 3725 m from the source. The seismogram and the reflections chosen for modeling are shown in Figure 5.3.

The test of the first hypothesis (Figure 5.4.a) shows that the first bottom return (B1) has 0 degree slope, suggesting a flat lake bottom. The inversion for the second chosen event (B2) gives the best correspondence with the observed travel times for a bed slope of -1 degree northward. Overall, these two reflections make a reasonable continuation of each other, while the other two (B3 and B4) suggest that the bottom would need change in elevation of at least ~ 110 m over the horizontal distance of 600 m (Figure 5.4.a), which does not seem to be realistic. Therefore, the conclusions from this hypothesis test are:

(1) the first return (B1) is the lake bottom, which is flat (0 deg) between the source and receivers;

(2) it is followed by a reflection (B2) from bed sloping 1 degree northward;

(3) the last two reflections considered are most likely not due to a non-flat bed (2D case).

The next hypothesis to test (3D case; Figure 5.4.b) was applied to the reflections B3 and B4 only. In this case the estimate can be done on the slope of the plane and its

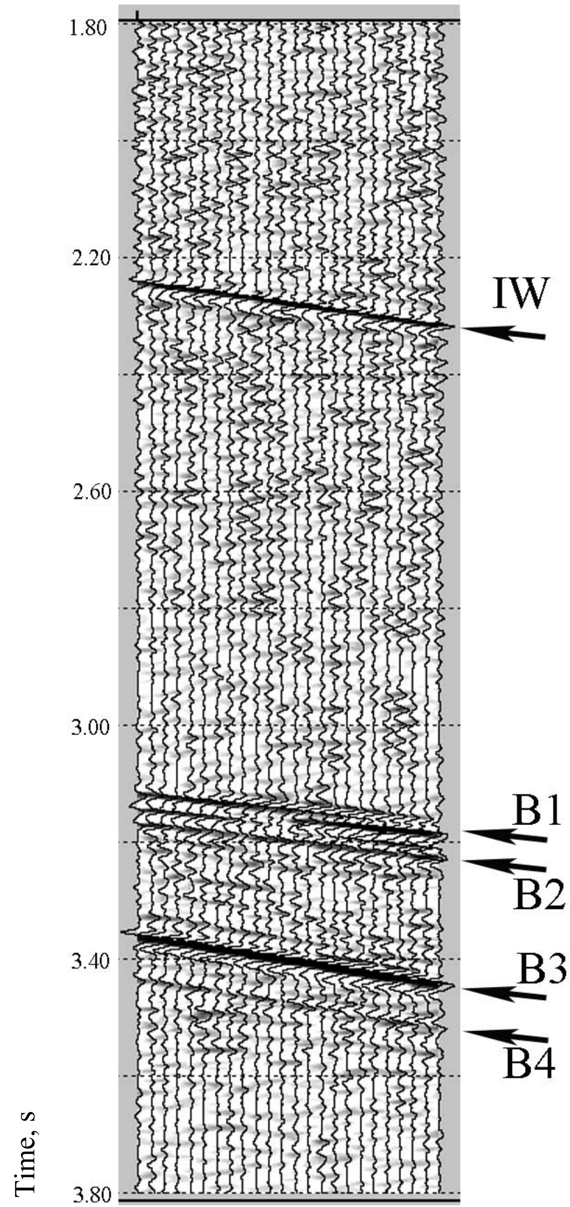
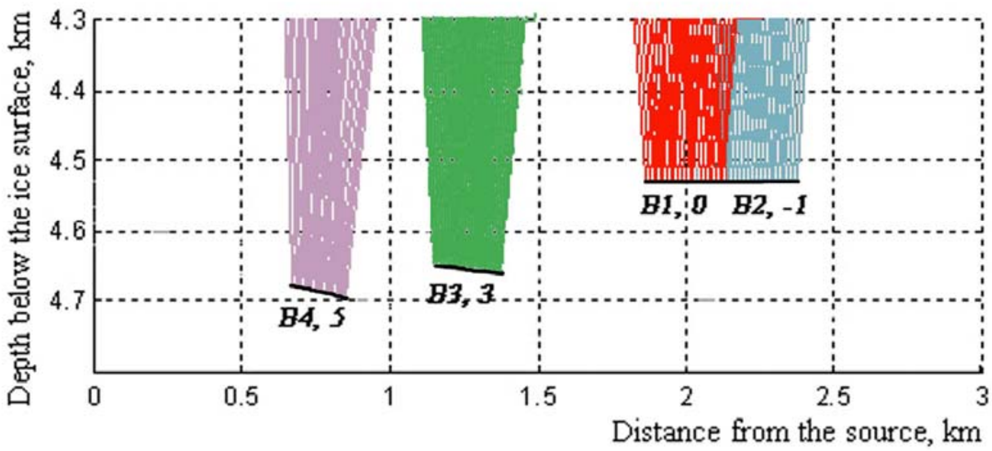


Figure 5.3 Recorded seismogram at the point 3CD with the reflection chosen for modeling labeled B1 through B4; IW is ice-water interface; WM is water reverberation. The vertical axis shows traveltime in seconds. The first offset is 3725 m away from the source.

a.



b.

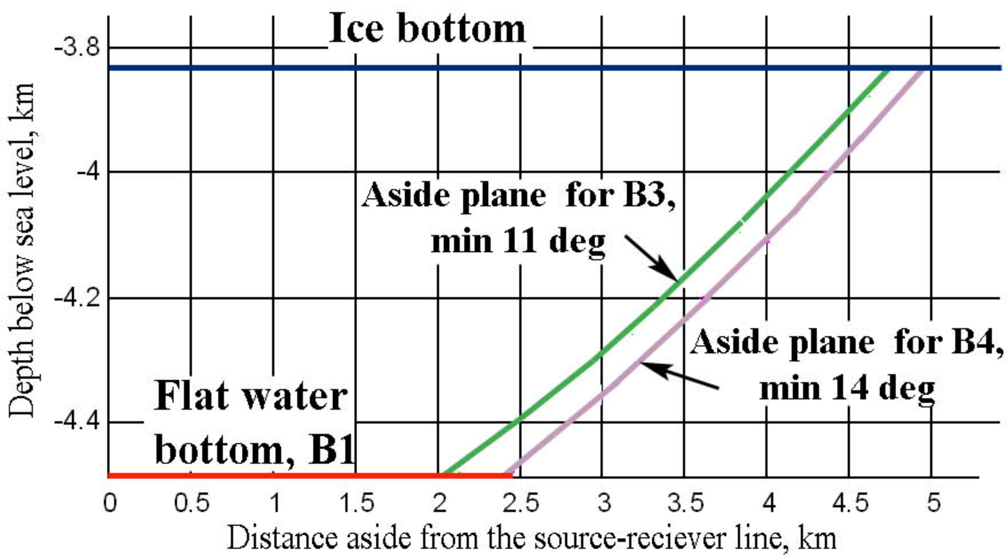


Figure 5.4 The tests of 2D and 3D hypotheses at the point 3CD

a. The test for a non-flat lake bottom (2D), showing the location of the water/basement boundary for all chosen reflections; the raypaths of different colors correspond to different reflections (see Figure 5.3); the number next to the reflection identification is the slope in degrees. The negative number corresponds to southward slope.
b. The test for a side echo for point 3CD, showing the location and a slope of the inclined plane aside of the SRL.

horizontal distance from the SRL. The estimates suggest that if reflections B3 and B4 are side echoes, their source should be located at least 2 km away from the SRL and should have a slope of at least 11 degrees for B3 and 14 degrees for B4.

The last hypothesis to test was the presence of the layer of unconsolidated sediments at the bottom of the lake. In this case the travel time inversion for the reflection B3 suggests the thickness of this layer to be 210 m for a seismic velocity in sediments of 1700 m/s and 240 m for a velocity of 1900 m/s. The reason for reporting two different possibilities here is that modeling with these velocities gives the same error between observed and estimated data. If the velocity in sediments increases, error increases too. Because of this, it is not possible to better resolve the velocity in the sediments, so the range is reported. Assuming a sedimentary layer, return B4 is in very good agreement with being the reflection from the bottom of the sedimentary layer northward of middle points of the SRL (the top of this layer is marked by reflection B2).

5.4.2 Seismogram 9S47

The point 9S47 (Figure 5.1) marks the maximum lake depth recorded so far. It corresponds to the small trough in the middle of profile across the lake (Masolov et al., 2006; Figure 3.5), which is ~ 400 m deep and ~ 5 km wide. The presence of this trough is confirmed with adjacent seismograms.

Four events were chosen for modeling (Figure 5.5). The following conclusions were made as a result of the first hypothesis test:

(1) the true lake bottom recorded in this seismogram is flat (0 degrees) and it is represented with the event B2;

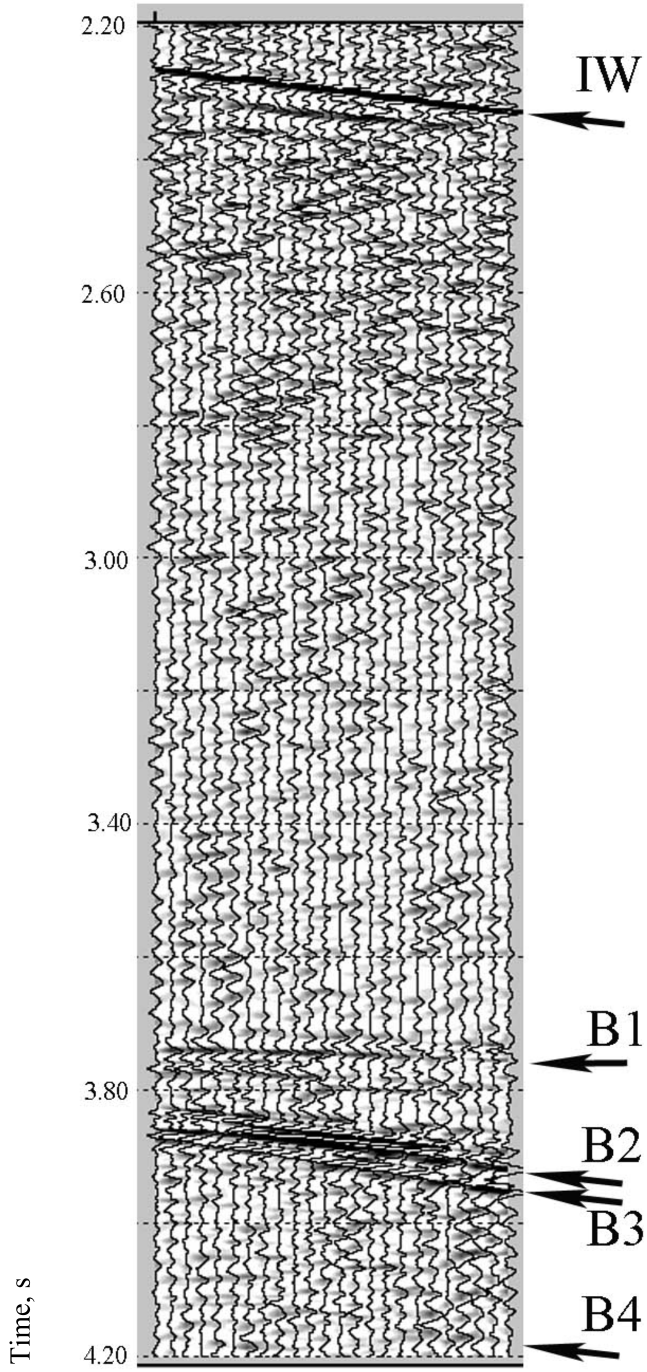


Figure 5.5 Recorded seismogram at the point 9S47 with the reflection chosen for modeling labeled B1 through B4; IW is ice-water interface; WM is water reverberation; the vertical axis shows traveltime in seconds. The first offset is 3355 m away from the source.

(2) two of the other reflections, B1 and B3, are in good agreement with the hypothesis of non-flat lake bottom (2D), while the last event (B4) is not.

Given this, the side echo hypothesis (3D case) was tested for B4 only. The result shows that for this event to be side echo, the reflector must be located at least 2.3 km away and have a slope of at least 11 degrees. If this is a reflection from the bottom of sedimentary layer, this layer should be 250 – 280 m thick and have a seismic velocity of 1700 – 1900 m/sec.

5.4.3 Seismogram 3DL

The distinct feature of seismogram 3DL (Figures 5.1 and 5.6) is that each reflection is followed by a ghost delayed by about 10 milliseconds. This seismogram shows the largest number of secondary bottom reflections among all records analyzed in this study. In total, only three of the most pronounced events were analyzed. The modeling shows that the first reflection after the ice-water interface (B1) is the flat lake bottom (slope of 0 degrees), while the two other chosen events (B2 and B3) are not consistent with the hypothesis of a non-flat lake bottom in 2D. The side echo test requires the reflector located at least 1.5 km away from the SRL on a plane sloped at least 8 degrees for B2 and 12 degrees for B3. If these two events represent sedimentary layers, each would have a thickness of about a hundred meters and a velocity of 1700 - 1900 m/sec in the upper layer (B2) and 1900 - 2100 m/sec at the bottom layer (B3).

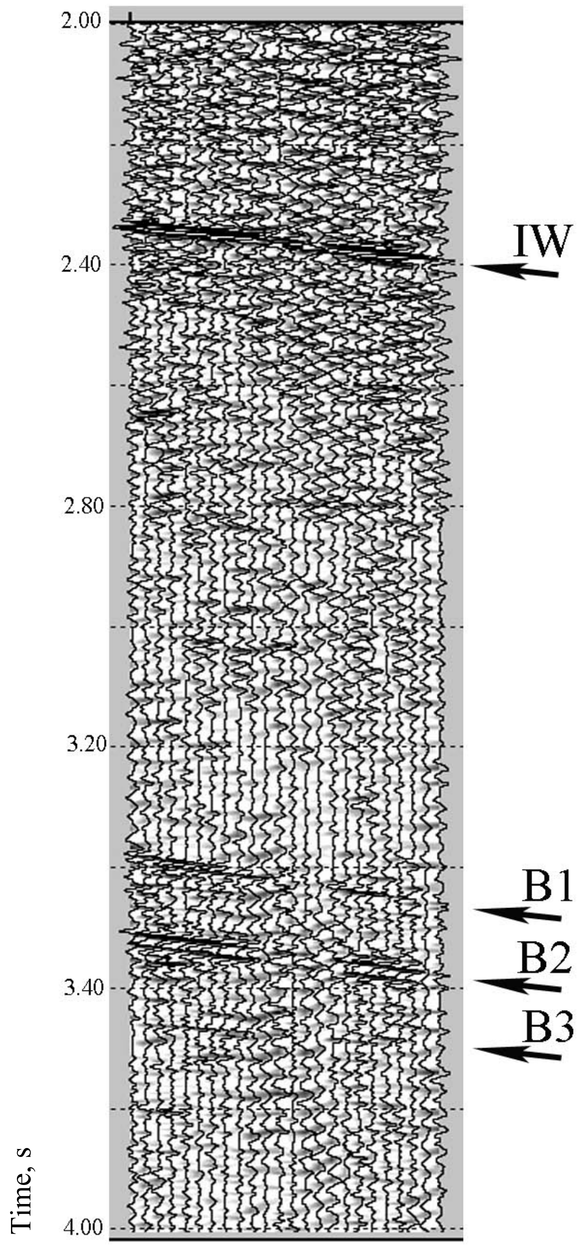


Figure 5.6 Recorded seismogram at the point 3DL with the reflection chosen for modeling labeled B1 through B4; IW is ice-water interface; WM is water reverberation; the vertical axis shows traveltime in seconds. The first offset is 3245 m away from the source.

5.4.4 Seismogram 6DL

The most northern seismogram analyzed was 6DL (Figures 5.1 and 5.7). This is the only data point located in the northern basin of Lake Vostok. The thickness of the sedimentary layer in this part of the lake was previously estimated to be about 50 m (Masolov et al., 1999), with the boundaries defined by reflections B1 and B2 (Figure 5.7). 2D modeling suggests that events B1 and B2 make a good continuation of each other with B2 being the flat lake bottom and B1 being a reflection from the non-flat lake bottom (slope of -1 degree, southward). The event B3 is not consistent with the hypothesis of a non-flat lake bottom in 2D, since it suggests a very sharp change in the bottom topography (slope of 5 deg at the distance 1 km from the flat lake bottom).

The estimate in 3D shows that for B3 to be a side echo it would be reflected from a plane sloped at least 11 degrees and located about 2.5 km away. For the sedimentary layer hypothesis, this event suggests a layer thickness of 350 - 380 m and a seismic velocity of 1700 - 1900 m/sec.

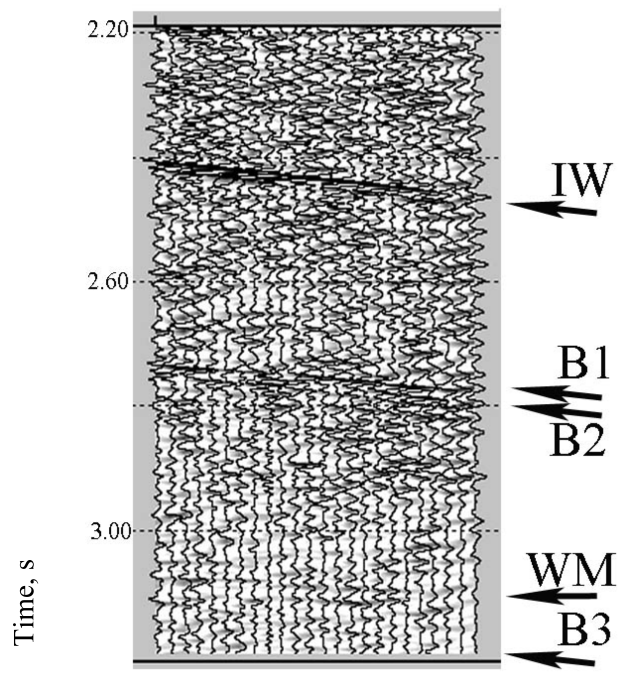


Figure 5.7 Recorded seismogram at the point 6DL with the reflection chosen for modeling labeled B1 through B4; IW is ice-water interface; WM is water reverberation; the vertical axis shows traveltime in seconds. The first offset is 3025 m away from the source.

5.5 Discussion

The comparison of all three hypotheses for the four seismograms studied here is shown in Table 5.1 and Figure 5.8. For all seismograms there was always an event that corresponded with a flat lake bottom. This reflection is not always the first after the ice-water interface. For three seismograms there was at least one reflection due to a non-flat lake bottom (2D case).

Table 5.1 Comparison of three tested hypotheses for the origin of the secondary bottom reflections in four seismograms analyzed in this study

Point	**Reflection**	**Bed geometry 2D**	**Side-plane slope (3D)**	**Sedimentary layer**
3CD	B1	Slope 0^o, lake bottom		
	B2	Slope -1^o, reflection from non-flat bed (2D), consistent with B1		
	B3	3^o at inconsistent depth	11^o at 2.1 km from 0^o	210-240 m
	B4	5^o at inconsistent depth	14^o at 2.4 km from 0^o	210 -240 m, the top of this layer is marked by reflection B2
9S47	B1	Slope -5^o, reflection from non-flat bed (2D), consistent with B2 and B3		
	B2	Slope 0^o, lake bottom		
	B3	Slope 4^o, reflection from non-flat bed (2D), consistent with B1 and B2		
	B4	2^o at inconsistent depth	11^o at 2.2 km 0^o	250-280 m
3DL	B1	Slope 0^o, lake bottom		
	B2	2^o at inconsistent depth	8^o at 1.5 km from 0^o	110-125 m
	B3	-2^o at inconsistent depth	12^o at 2 km from 0^o	94-104 m
6DL	B1	Slope -1^o, reflection from non-flat bed (2D), consistent with B2		
	B2	Slope 0^o, lake bottom		
	B3	5^o at inconsistent depth	11^o at 2.7 km from 0^o	350-380 m

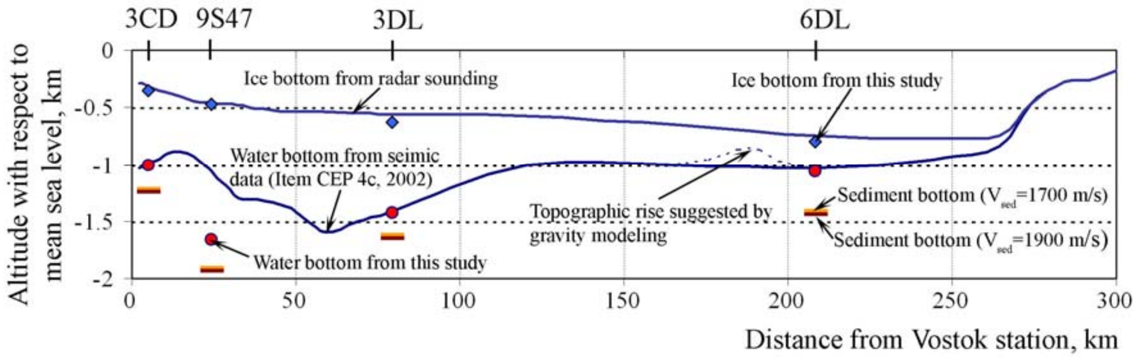


Figure 5.8 The cross-section along the lake (data from Item CEP 4c, 2002) with the results of this study. The location of the profile is shown in Figure 5.1. Note that point 9S47 is located 10 km to the west of the profile.

The hypothesis of a side echo in all locations gave a significant slope (8 - 14 degrees) of a reflector to the side of the seismic line. Slopes like these would be typical for areas close to the coast line of the lake, while all of the data points were located at a significant distance from the coast line. Also, the 2D hypothesis test suggests that there is always a reflection corresponding to the flat (0 deg) lake bottom, so such a sharp change in the topography over relatively short distance is not very realistic. For this reason, the sharp bed slopes (8 degrees and higher) are discounted.

The last hypothesis tested was the presence of a sedimentary layer at the bottom of the lake, which is consistent with all four seismograms. This suggests the presence of at least 200 m of unconsolidated sediments at the bottom of the lake. The sedimentary layer hypothesis indicated a consistent seismic velocity of 1700 to 1900 m/sec for this layer, which is reasonable for unconsolidated sediments. The only seismogram analyzed in the northern basin showed a thicker sedimentary layer than in the southern basin. The only seismogram in the middle of the lake shows the stratigraphy of the sedimentary layer with the upper hundred meters of sediments having seismic wave velocity of

1700 - 1900 m/sec underlain by a hundred meter layer with a velocity of 1900 - 2100 m/sec.

5.6 Summary

Four seismic records in different parts of Lake Vostok were analyzed. Three different hypotheses were tested for the origin of secondary seismic reflections at the bottom of Lake Vostok. The results show that some of the reflections, but not all of them, are consistent with the hypothesis of a gently sloping (< 2 degrees) non-flat lake bottom. The rest of the reflections were tested as side echoes, but this was rejected because of unreasonably steep slopes (at least 8 degrees required) at the lake bottom. The hypothesis that is the most compatible with all analyzed seismograms is the presence of a layer of unconsolidated sediments at the bottom of Lake Vostok. The modeling suggests the presence of an ~200 m thick sedimentary layer with the seismic velocity of 1700 - 1900 m/sec in the southern and middle parts of the lake. The sedimentary layer thickens to ~350 m in the northern basin.

Chapter 6: Improved bathymetry and sediment distribution in Lake Vostok: implication for pre-glacial origin of the lake

6.1 Objectives for the study and available data

Subglacial Lake Vostok of East Antarctica attracts much attention from the scientific community due to its uniqueness and possibly life-supporting environment (Karl et al., 1999). The north-dipping lake ceiling causes the temperature/pressure conditions to vary across different parts of the lake (Kapitsa et al., 1996; Siegert et al., 2000 and 2001; Studinger et al., 2003). Those differences trigger melting at the ice-water interface in the northern part of the lake but freezing of the lake water onto the bottom of the ice sheet in the southern part of the lake. Such a distribution of melting/freezing patterns, in turn, is responsible for generating water circulation within the lake (Siegert et al., 2000 and 2001; Thoma et al., 2007). All of these internal processes within Lake Vostok are subject to numerical modeling, as in Williams (2001) and Thoma et al. (2007). The key 'a priori' information for such modeling is the 3D geometry of the lake, which infers both spatial and depth distribution of water as well as unconsolidated sediments at the bottom of the lake. The lake's coast line is well mapped by radar sounding data (Figure 2.7.b), providing the spatial constraints for both water and sedimentary layers.

The precise knowledge of the lake's bathymetry is a necessary component of the numerical modeling of water circulation and mixing in the lake, as well as the interaction between the lake and the overlying ice sheet. The earliest 3D bathymetry model was proposed by Williams (2001) based only on a seismic water measurement beneath Vostok station. Other two known 3D models of the Lake Vostok bathymetry (Studinger et al., 2004, Figure 3.9; Roy et al., 2005, Figure 3.1) are based on airborne geophysical data, collected by the University of Texas Institute for Geophysics (UTIG) during 2000-

2001 field season (Richter et al., 2001; Studinger et al., 2003; Holt et al., 2006), constrained with seismic data available at the time. Both of these models (see the description of those in Chapter 3) still have some discrepancy between seismic and gravity derived water thickness.

Whether Lake Vostok existed before the current glaciation is unknown. Kapitsa et al. (1996) proposed that the melting of the overlying ice is the source of the water in Lake Vostok, inferring that the lake was formed after the current ice sheet covered the lake. Duxbury et al. (2001) applied a 1D thermodynamical model and concluded that a pre-glacial lake would have survive the glaciation without being frozen to the bottom if the water thickness in the lake exceeded 53 m. This hypothesis is criticized by Siegert (2004, 2005), proposing that even if the lake existed before the glacial advance, it would be completely frozen during the onset period of glaciation, which again is rebutted by numerical modeling by Pattyn (2004). Thus, the question whether the lake existed before glaciation is still a matter for debate.

The objectives of this research are (1) to present a new model of lake's bathymetry along with the distribution of unconsolidated sediments at the bottom of the lake, based on 3D inversion of the same gravity dataset used in Roy et al. (2005) and Studinger et al. (2004), constrained with seismic soundings available to date, (2) to compare and contrast the new model with previous models, and (3) to estimate sedimentation rates and times for six possible mechanisms capable of depositing unconsolidated sediments at the bottom of the lake in order to reveal the age of the lake.

The reduction of the gravity data used in Roy at al. (2005) and this study was performed at UTIG (Holt et al., 2006) with a reported RMS of the differences at the crossover points for the gravity grid after the leveling of 1.2 mGal. Studinger et al. (2004) uses the reduction algorithm based on Childers et al. (1999) and reports the standard deviation of the adjusted crossover error of 2.7 mGal. The regional trend (Figure 3.3) was removed from the reduced free-air anomaly before the inversion. The resultant residual anomaly is shown in Figure 3.7.

The available seismic soundings (Masolov et al., 1999 and 2006; Item CEP4c, 2002) were used both to constrain the model and to validate the results (Figure 6.1). The most dense seismic coverage is available near Vostok station, where the seismic soundings are several hundreds meters apart, revealing the presence of a relatively small (about 5 km across and 690 m deep) basin filled with 350 m of sediment beneath Vostok station (Profiles AB and 1-1' in Figure 2.4; Masolov et al., 1999; Item CEP 4c, 2002). Seismic data suggests the lake is deeper in the southern part with the maximal water thickness of 1200 m (Profile S47 in Figure 2.5; Item CEP4c, 2002; Masolov et al., 2006); the water thickness decreases up to 250 m at the north of the lake (Profile 1-1' in Figure 2.4.b). The seismic soundings that are less than 5 km from each other (blue dots in Figure 6.1) were ignored, so only 60 seismic soundings were used during the inversion of airborne gravity data (red dots in Figure 6.1).

Unconsolidated sediments at the bottom of Lake Vostok were identified based on interpretation of seismic data (Chapter 5; Filina et al., 2007a), revealing the existence of up to 270 m of unconsolidated sediments in the southern part of the lake and 350 -380 m in the northern basin.

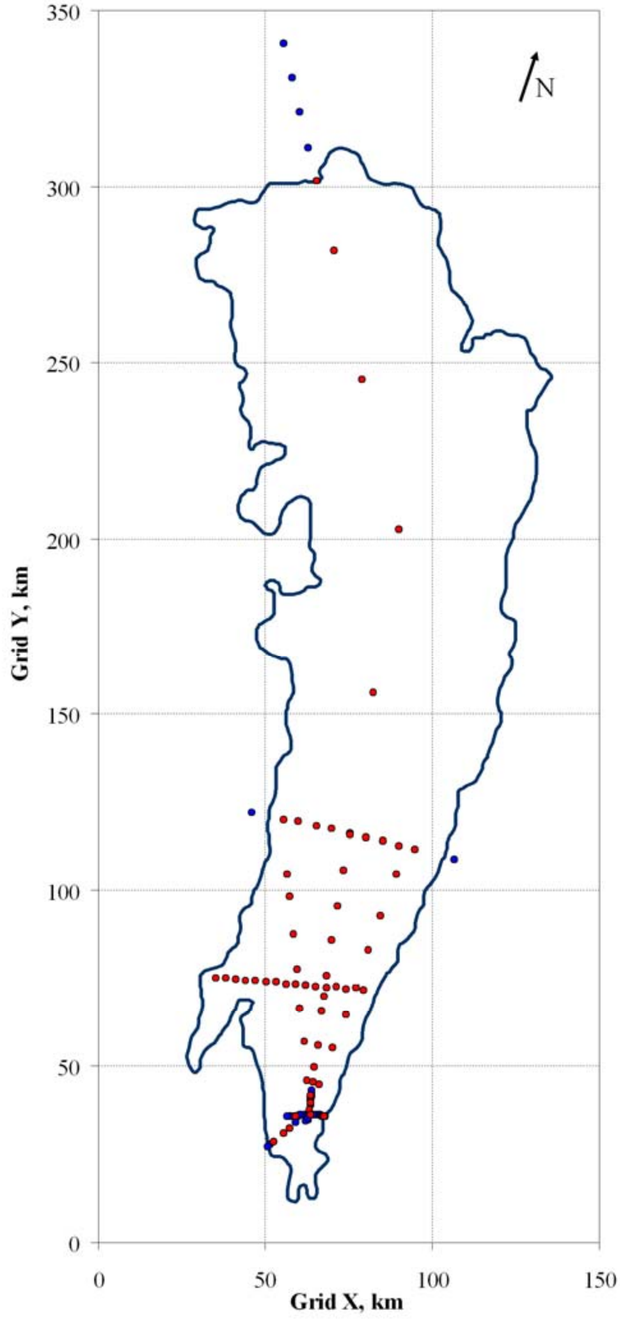


Figure 6.1 Location of seismic points used to constrain the revised 3D model and to validate the results (red dots). Blue dots show seismic soundings that were ignored since they are either outside of the lake area, or are located at the distance of less than 5 km from other soundings.

6.2 New 3D bathymetry and unconsolidated sediment distribution

All available airborne data were interpolated into a regular grid with a 5 km cell, which is smaller than the estimated resolution of gravity data for the survey parameters used (~7.2 km based on Childers et al., 1999; Holt et al., 2006). The model was composed of water (density of 1000 kg/m^3) and sediment layers (assumed density of 1850 kg/m^3) overlying bedrock with a density of 2550 kg/m^3. The forward problem was solved based on the equation of Parker (1973):

$$F[g] = 2\pi G e^{|k|Z_0} \sum_{n=1}^{\infty} \frac{(-|k|)^{n-1}}{n!} F\left[\Delta\rho(Z_1^n - Z_2^n)\right]$$

where g is gravity anomaly,

G –gravitational constant,

$\Delta\rho$ is density contrast with surrounding rocks,

Z_0 – anomaly level (the flight elevation),

k – wavenumber,

Z_1 and Z_2 are confining surfaces.

The inversion was performed by a conjugate gradient method (Tarantola, 1987). The new bathymetry model of Lake Vostok (Figure 6.2.a) has a maximal water thickness of 1100 m in the southern basin, showing very good correlation with seismic data.

The inversion was also performed using VFSA algorithm (Sen and Stoffa, 1995) as in Roy et al., 2005. The results of inversions with conjugate gradient and VFSA algorithms correlate very well with the mean value of the difference between the two results being less than 3 meters for both water and sedimentary layers. Such a good match infers that the global minimum was achieved during the inversion.

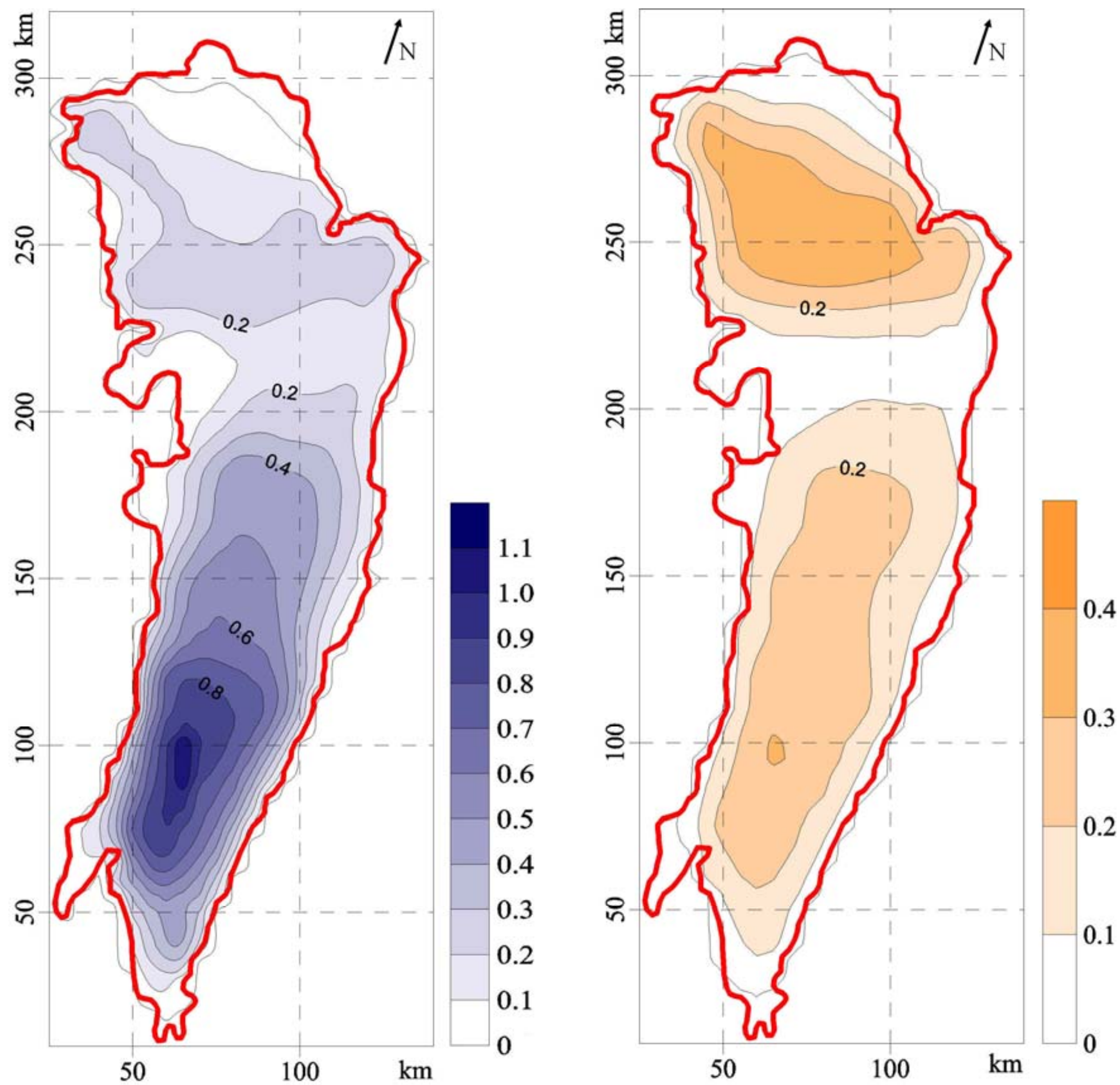


Figure 6.2 The results of the revised inversion of airborne gravity data

a. the water thickness in km derived from gravity inversion; contour interval (CI) is 0.1 km; red line shows the lake's coastline from radar data;
b. the sediment thickness (km); CI is 0.1 km;

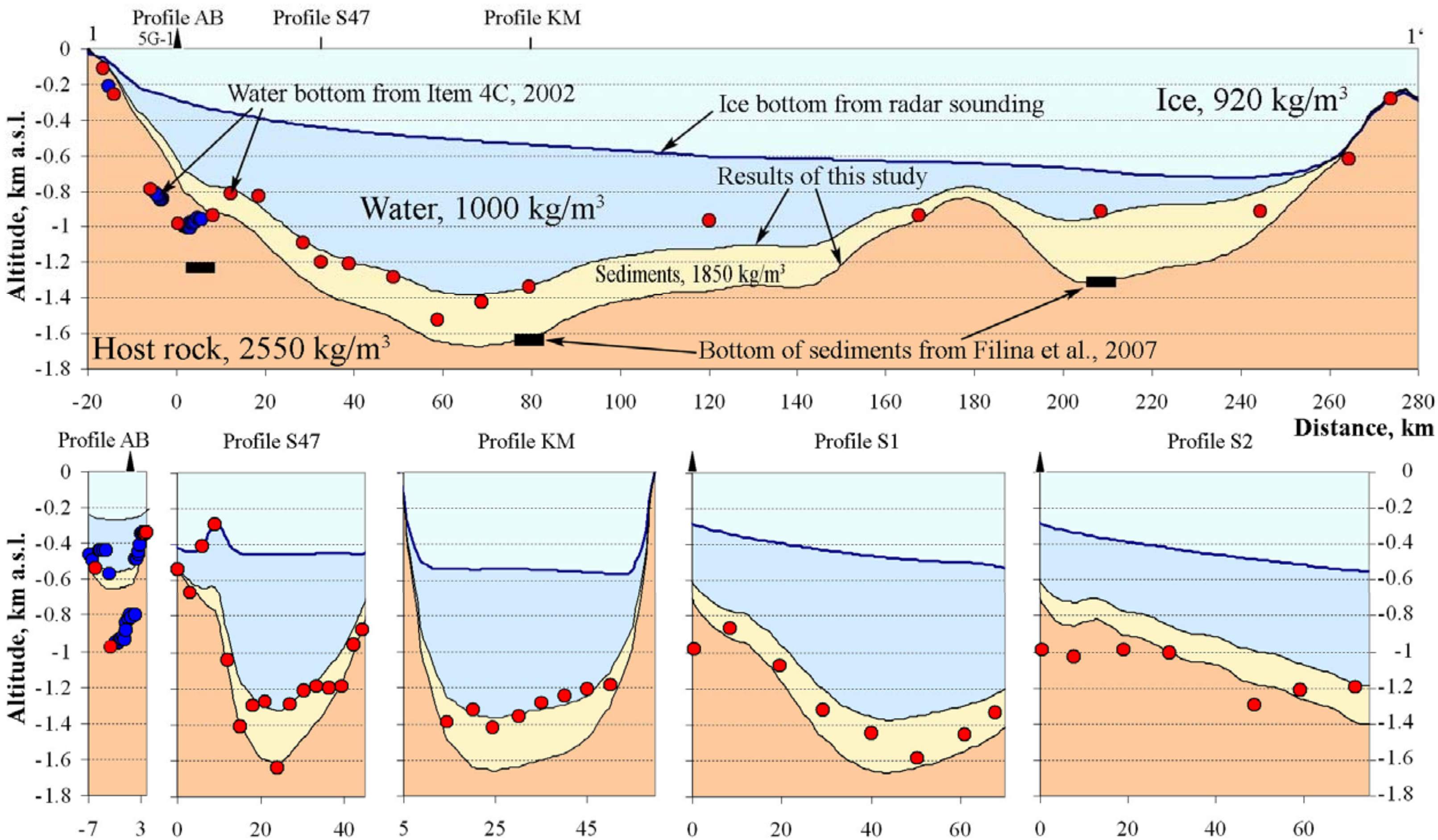


Figure 6.3 Comparison of the revised model with seismic data. Red dots show the bottom of the lake form seismic data used to constrain the model and to calculate the RMS of the difference between gravity derived water thickness and seismic data (for location see Figure 6.1); blue dots are seismic data that were ignored since they are less than 5 km apart. Black rectangles on the profile1-1' show the bottom of sedimentary layer from Filina et al., 2007a (Chapter 5). Black triangles are 5G-1 borehole at Vostok station.

Since many seismic soundings are located near Vostok Station just several hundreds meters from each other (blue dots in Figures 6.1 and 6.3), only 60 points located at least 5 km apart (red dots in Figures 6.1 and 6.3) were used both to constrain the model as well as to verify the results. The RMS of difference between water thicknesses derived from seismic data and gravity modeling is 125 m. In the northern basin the water depth is 280 m. The thickness of the inverted sedimentary layer (Figure 6.2.b) is up to 300 m in the southern basin and 400 m in the northern one, which is also consistent with the seismic data (Filina at al., 2007a).

6.3 Discussion on bathymetry and sediment distribution models of Lake Vostok

The gravity anomaly is a function of the anomalous mass geometry and its density contrast with the host rock. The proposed model for Lake Vostok consists of water and unconsolidated sedimentary layers overlying the host rock. The water density of 1000 kg/m^3 was used in this study. The densities of unconsolidated sediments and the host rocks should be properly chosen and fixed during inversion. In this study, sediments at the bottom of the lake were chosen to have density of 1850 kg/m^3, which is a consistent value for water-filled unconsolidated sediments.

Previous 2D gravity modeling of Lake Vostok showed the best agreement between water thicknesses derived from seismic soundings and from gravity inversion if the density of 2550 kg/m^3 was used for host rocks (Filina et al., 2006a). The chosen density of 2550 kg/m^3, typical for consolidated sedimentary rocks, is also consistent with the observed sedimentary rock inclusions trapped in the ice beneath Vostok Station (Leitchenkov et al., 2007), as well as with the model of Studinger et al. (2003b), where the presence of a sedimentary basin beneath Lake Vostok was suggested. If the density of 2670 kg/m^3 is used during modeling, the lake's depth decreases by about 200 m. This is one of the possible explanations for the lake appearing to be shallower (up to 800 m) in Studinger et al. (2004) model than it actually is (up to 1200 m based on seismic soundings), since Studinger et al. (2004) utilizes density of 2670 kg/m^3 for the host rock. The new estimated water volume for Lake Vostok is 5000 ± 950 km^3 in contrast to 5400 ± 1600 km^3 estimated by Studinger et al. (2004). In spite of the new bathymetry models indication of a thicker water layer in the southern basin, the total water volume in the lake decreases by about 8% due to much shallower water thicknesses (up to twice the previous estimates) in the middle and northern parts of the lake.

Another reason for the discrepancy in water thickness derived from the Studinger et al. (2004) gravity inversion and seismic soundings is the omission of a layer of unconsolidated sediments. Based on the seismic soundings, the layer of unconsolidated sediments in the northern basin appears to be thicker than the water layer (350 – 380 m of sediments vs. 250 m of water). Those sediments are responsible for a gravity effect up to 8 mGal, which exceeds the accuracy of the gravity data by several times. That is why the sedimentary layer cannot be ignored during modeling.

The model of Roy et al. (2005) includes the presence of the sediments at the bottom of the lake, although its thickness was constrained based on the distribution reported in Masolov et al. (1999). The most probable reason for the disagreement of inverted water thickness with seismic data in Roy et al.'s (2005) model is the use of a linear regional trend. This also resulted in a spatial discrepancy with the lake's coastline.

A comparison of 3D bathymetry/sediment models for Lake Vostok is shown in Table 6.1. Only the seismic model represents the small basin beneath Vostok station, which is up to 690 m deep, about 20 km long and 5 km wide. The dimension of this basin is smaller than the resolution of this airborne gravity dataset (Childers et al., 1999; Holt et al., 2006) and demonstrates the resolution limits of gravity derived bathymetry models.

Table 6.1. Comparison of 3D bathymetry/sediment models for Lake Vostok

	Water thickness in the southern basin	Water thickness in the northern basin	Sediment thickness	Number of seismic points used and RMS
Seismic data	1200 m	250 m	Up to 380 m	----
Williams (2001)	510 m	Not existent	Not included in the model	----
Roy et al. (2005)	~ 1000 m	~ 800 m	Up to 250 m	Not reported
Studinger et al. (2004)	~ 800 m	~ 450 m	Not included in the model	19 points, 250 m
This study	1100 m	280 m	Up to 400 m	60 points, 125 m

6.4 Sedimentation processes in Lake Vostok

Our bathymetry/sediment model confirms the presence of a layer of unconsolidated sediments at the bottom of Lake Vostok revealed from seismic data (Filina et al., 2007a). The total volume of sediments is estimated to be 2600 km^3. Possible sedimentation mechanisms are:

(1) sediments may be deposited as a result of fluvial processes in the assumption that the lake existed before the current glaciation, so the observed sediment may be deposited either entirely or partially before the glaciation;

(2) sediments may be deposited as a result of periglacial processes at the onset of a glacial advance;

(3) sediments can melt out of the overlying ice sheet;

(4) sediments may be scoured from the rocks beneath the ice, transported and deposited into the lake by the overriding ice;

(5) suspended sediments may be transported and deposited by water flowing into the lake as a part of the subglacial hydrological system;

(6) suspended sediments may be deposited by periodical subglacial outbursts.

Our inversion of gravity data shows that sediments are not equally distributed over the lake's bottom (Figure 6.2.b). The larger and deeper southern basin with an estimated area of 10000 km^2 holds ~1400 km^3 of sediments (up to 300 m thick layer), while ~1200 km^3 of sediments (up to 400 m thick) are located in the smaller and shallower northern basin with a surface area of approximately 7000 km^2.

It would be logical to assume that if the lake existed before glaciation and the sedimentation rate was constant over the entire lake, the sediments would be either equally distributed, or the deeper basin would be filled with a thicker sedimentary layer. The observed distribution is the opposite. The possible explanations for this are:

(1) The sedimentation rate was/is higher in the northern portion of the lake than it is in the southern one;

(2) The sedimentation rate was/is the same throughout the lake, but there is an internal water circulation within the lake that redistributes the sediment, so the observed sediment distribution takes place. This hypothesis assumes that strong northward currents should exist inside the lake that should be capable of transporting significant amounts of sediments from the deeper southern part upward to the shallower northern basin. Those sediments can be transported both as a suspended load and as a bedload. It is known that for suspended sediments to be deposited, the energy of the environment should be very low, i.e. no currents should be present. So, if this is the case, a strong current should exist, which transports suspended sediments from the southern basin to the northern one. This current must be shut off completely in the northern basin. If the extra ~100 m sediments in the northern portion were transported as a bedload, the energy of water should be very

high to be able to carry relatively heavy particles upward. In this case, the energy of the carrying current should decrease in the northern basin, so that the transported sediments could be deposited. If this is the case, a total volume of 300 km^3 of sediments (equal to a ~100 m thick layer across the lake) should be transported and deposited by the mean of the northward current. This northward pattern contradicts to the numerical modeling performed by Thoma et al. (2007), suggesting that flows at the bottom layer of the lake are oriented in a southeast direction.

(3) The sedimentation was initially the same throughout the lake area, but later some changes occurred in the system and the sedimentation in the southern part either decreased or was shut down completely compared to the sedimentation rate in the northern part. This scenario is consistent with the hypothesis that the lake existed before glaciation and some sediment but not all were deposited before the ice sheet came. After the lake was covered with ice, the currently observed pattern of freezing at the south and melting at the north of the lake took place. The freezing in the southern basin shut off the sediment input into the lake since, instead of being carried with the moving ice sheet and getting dumped into the lake, sediments remained frozen at the ice bottom (Leitchenkov et al., 2007). In contrast, the melting in the northern basin does not prevent sediment input in the lake. Instead, the sediments may also melt out from the overriding ice. In this case the assumption should be made that basal freezing takes place somewhere to the west (upstream) of the lake, so the sediments get incorporated into the ice sheet.

6.4.1 Was the lake filled with the observed amount of sediments before glaciation?

The first scenario assumes that Lake Vostok existed before the glaciation, and all sediments were deposited before the lake was covered with ice. This hypothesis is consistent with Duxbury at al. (2001), suggesting that the lake may have remained unfrozen during the transition to the glacial period if the water thickness exceeded 53 m. The seismic soundings and gravity modeling show that the current water thickness of Lake Vostok exceeds 1000 m. So based on the model of Duxbury et al. (2001), Lake Vostok should not freeze to the bottom during the current glacial event.

For the first mechanism (Table 6.2), the sedimentation with fluvial processes with the rate of 0.035 cm/yr as in subaerial Lake Baikal (Edgington et al., 1991) may be assumed, which is also consistent with the sedimentation rates observed in Lake Michigan (Robbins, 1975). If this is the case, Lake Vostok should have existed for about 500 ky before glaciation to collect 2600 km^3 of sediments at the bottom.

The faster deposition of a thick layer of unconsolidated sediments at the bottom of pre-glacial Lake Vostok may occur in the assumption of periglacial processes just before the onset of glaciation. The sedimentation rate is significantly higher in this case, increasing up to 10 cm/yr (Hallet et al., 1996) such as currently observed for large and fast-moving temperate valley glaciers of southeastern Alaska. In this case only 1.8 ky are required to deposit all the observed sediments at the onset of the glacial advance.

In both these cases, the sedimentation is assumed to be shut off by the glaciation. The thicker sedimentary layer in the northern basin may be explained with the different sedimentation rates for different parts of the lake. This is consistent with the observation of the subglacial topography being generally higher in the northwestern part of the survey area, so the periglacial sedimentation rate should be higher in the northern basin. Another explanation would be the presence of the northward oriented currents at the lake's bottom

Table 6.2 The estimated time to deposit observed sediments at the bottom of Lake Vostok: assuming that all sediments were deposited before the current glaciation

Assumed sedimentation mechanism	**Assumptions**	**Time**
Sediments brought with fluvial system(s)	• Sedimentation rate is 0.035 cm/yr that is currently observed value for Lake Baikal (Edgington et al., 1991)	~500 ky
Sediment deposited as a result of periglacial processes	• Sedimentation rate of 10 cm/yr as for the fast-moving temperate valley glaciers of southeast Alaska (Hallet et al., 1996)	1.8 ky

that were responsible for redistributing of sediments along the lake's bottom, in assumption that there was an equal sediment supply for both basins.

6.4.2 Was the lake partially filled with unconsolidated sediments before glaciation?

If Lake Vostok existed before glaciation, some of the sediments, but not all of them, may be deposited pre-glacially by the mechanisms described above. In this scenario a 300 m thick uniform sedimentary layer (i.e. the southern basin observation) is assumed to be deposited before the glacial event in both basins of the lake. After the lake was covered with ice, the currently observed pattern of freezing at the south and melting at the north of the lake was developed (see Figure 2.7.b). The sediment input in the southern basin was shut off after glaciation due to freezing at the bottom of the ice in that area. The rest ~100 m of sediments in the northern basin were deposited during the glaciation, which is equivalent to 300 km^3 of sediments.

Two possible sedimentation mechanisms for the partial sedimentation were assumed (Table 6.3). The first mechanism considered assumes that sediments melt out from the overlying ice sheet. The estimate for this meltout was made with the following assumptions:

(a) the total amount of sediment that melts out from the overriding ice sheet may be estimated based on the average concentration of sediments in the top 70 m of the accreted ice observed in the ice core drilled at Vostok Station (Jouzel et al., 1999; Royston-Bishop et al., 2005; Leitchenkov et al., 2007; Appendix 4);

(b) each visible inclusion grain was assumed to be a sphere of 2 mm diameter. The concentration of sediments in the ice, then, may be estimated based on the known number of inclusions in the ice core (Jouzel et al., 1999; Figure 2.2.c; Appendix 4);

(c) the melting rate in the northern basin has been constant since the beginning of the glacial period and is constant for the entire basin with the value of 2 cm/yr (Siegert et al., 2000);

(d) the current velocity of the ice sheet observed at Vostok station (3 m/yr, Chapter 2) is constant for the entire lake region as well as having been constant during the entire period of glaciation.

Assumptions (a) and (b) give an estimated average concentration of sediments in the top 70 m of the accreted ice of $3.6 \cdot 10^{-6}$ (Appendix 4). If it is conservatively assumed that the glacial period lasted 30 Myr (Duxbury et al., 2001), the sedimentation rate needs to be $140 \cdot 10^{-6}$ cm/yr to deposit a 100 m thick layer of sediments in the northern basin.

Table 6.3 Estimated sedimentation rate and time required to deposit 100 m thick layer of sediments in the northern basin. This scenario assumes that the uniform 300 m thick layer of sediments was deposited at the bottom of pre-glacial Lake Vostok, while the post-glacial sedimentation is possible in the northern basin only (see text for details)

Sedimentation mechanism	**Assumptions**	**Estimated sedimentation rate, cm/yr·10^{-6}**	**Time required to deposit 100 m of sediments**
-------	• Glaciation lasts for 30 MA; • 300 km^3 were deposited in the northern basin only (equal to 100 m thick layer), since the freezing in the southern basin prevents sedimentation;	140	-------
Sediment melt out from the overlying ice sheet	• Valid in the northern basin only; • Sediment concentration is $3.6 \cdot 10^{-6}$ (Appendix 4).	7.2	635 Myr
Sediments are brought with the moving ice	• Valid in the northern basin only; • Sediment concentration is $16 \cdot 10^{-6}$ (Appendix 4).	0.07	67 Byr

The estimated sedimentation rates for the meltout mechanism (Table 6.3) is $7.2 \cdot 10^{-6}$ cm/yr, suggesting that it is not capable of depositing even a 100 m thick layer of unconsolidated sediments in the northern basin during glaciation.

The estimate for the deposition rate for the sediments that were scoured, transported and dumped in the lake by the overriding ice (Table 6.3) is more tenuous. It was assumed that in the southern basin all of the sediments that are brought with the moving ice and dumped in the lake, get quickly frozen at the ice bottom largely over the shallow water adjacent to the coast upstream of Vostok ice core, as in Leitchenkov et al., (2007). In contrast, in the northern basin it was assumed that the same amount of sediments is brought with the moving ice and dumped in the lake, but instead of being frozen to the ice bottom those sediments get deposited at the bottom of the lake. The sedimentation rate due to this mechanism (Table 6.3) was estimated based on the following assumptions:

(a) the amount of sediments dumped in the lake by the overriding ice is equal to the maximal number of inclusions observed in the ice core drilled at Vostok Station (30 inclusions with an assumed diameter of 2 mm (as above) over one meter of ice core; Figure 2.2.c; Jouzel et al., 1999), which corresponds to a sediment concentration of $16 \cdot 10^{-6}$ (Appendix 4);

(b) the approximate length of the margin along which the deposition is occurring is 100 km;

(c) the ice has been moving to the northern basin with an assumed constant velocity of 3 m/yr (as above).

The estimated sedimentation rate for this mechanism is $0.07 \cdot 10^{-6}$ cm/yr, which is insufficient to supply even the 100 m of sediments in the northern basin. This estimate above is based on two major assumptions; i.e., (i) sediment transported at the bottom of the ice is the same for both lake basins, and (ii) all sediments that are dumped in the lake in the southwestern portion get frozen at the bottom of the ice. Both of those assumptions are vague; however, the estimated sedimentation rate of $0.07 \cdot 10^{-6}$ cm/yr suggests that the amount of the sediments brought with the ice needs to be at least three orders of magnitude higher for this mechanism to deposit a 100 m thick layer of sediments in the northern basin over 30 Myr.

6.4.3 Was the lake formed after glaciation?

This scenario also implies that even if the pre-glacial Lake Vostok existed and some sediments were deposited at its bottom, those were scoured and removed completely by the grounded ice at the onset of glaciation. In this case, to deposit the observed 2600 km^3 in Lake Vostok over the glacial period of 30 Myr long, the sedimentation rate should be $510 \cdot 10^{-6}$ cm/yr, which is two orders less than the one currently observed for the subaerial lakes (Edgington et al, 1991; Robbins, 1975).

Two other possibilities for depositing sediments under glacial conditions include deposition of suspended sediments from a subglacial hydrological network as suggested in Exploration of Antarctic Subglacial Aquatic Environments (2007), or as a result of numerous subglacial outbursts as suggested in Wingham et al. (2006). The estimates for those (Table 6.4) were made based on the assumption that the lake was developed after the glaciation, as suggested by Kapitsa et al. (1996) and Siegert (2005).

Table 6.4 The estimated time to deposit observed sediments at the bottom of Lake Vostok: assuming that all sediments were deposited after the current glaciation

Assumed sedimentation mechanism	**Assumptions**	**Estimated sedimentation rate, cm/y·10^{-6}**	**Time required to deposit 3000 m^3 of sediments**
--------	• The glacial period lasts 30 Myr;	510	--------
Suspended sediment transported and deposited by water flowing into reservoir	• Water influx is estimated to be 1.9 m^3/s; • Concentration of sediments is 0.001 by volume (Exploration of Antarctic Subglacial Aquatic Environments, 2007);	350	44 Myr
Suspended sediments deposited by periodical subglacial outburst	• Each outburst event last for one year with the discharge rate of 50 m^3/s (Wingham et al., 2006); • Concentration of sediments is 0.001 by volume (Exploration of Antarctic Subglacial Aquatic Environments, 2007); • The period of the event is 27 yr based on the availability of the upstream subglacial water.	9400 every 27 yr	44 Myr

In the assumption that the sediment precipitates from the suspended load of the subglacial water system, the total volume of the subglacial water available upstream of Lake Vostok needs to be estimated. The lake is located at a distance of ~200 km from Ridge B (see Figure 1.1 for location), so the catchment area may be conservatively estimated as a product of that distance and the lake's length (~300 km) perpendicular to the ice flow from that ridge. If bottom melting of 1 mm/yr is assumed (Kapitsa et al., 1996) for the entire catchment area, the estimated water flux through Lake Vostok is

0.06 km^3/yr or 1.9 m^3/s. This water flux is almost twice as large as the one assumed in Chapter 2 of Exploration of Antarctic Subglacial Aquatic Environments (2007), which suggested water flux of 1 m^3/s for Lake Vostok with most of it attributed to roof melting. If the sediment concentration of 0.001 by volume is assumed as in Exploration of Antarctic Subglacial Aquatic Environments (2007), the sedimentation rate for the flux of 1.9 m^3/s is $350 \cdot 10^{-6}$ cm/yr and it takes 44 Myr to fill Lake Vostok with the observed 2600 km^3 of sediments.

If we assume that 300 m of sediments existed at the bottom of the lake before glaciation (as mentioned in the previous section), and that only 300 km^3 (equivalent to 100 m thick layer of sediments) in the northern basin are deposited by this mechanism, it would take 5 Myr. In this case the sediments should enter the lake from the northern part, which is consistent with Figure 2.10 of Exploration of Antarctic Subglacial Aquatic Environments, 2007. The water flow should decrease significantly, so the particles that were carried in suspension may be deposited in the northern basin.

Another possible mechanism of sedimentation is deposition during periodical subglacial outbursts, as the one described by Wingham et al. (2006), which reports a discharge of 1.8 km^3 of water over a 16 month period. That event occurred in East Antarctica in the vicinity of the Adventure subglacial trench (see Figure 1.1 for location). The peak discharge rate in that event was estimated to be 50 m^3/s. This scenario is believed to be unlikely for Lake Vostok (Exploration of Antarctic Subglacial Aquatic Environments, 2007).

If deposition through a series of subglacial outbursts is assumed, a discharge rate of 50 m^3/s and a duration of each event of one year may be assumed as in Wingham et al. (2006), suggesting that 1.6 km^3 of water flows through Lake Vostok during one outburst event. Averaged over time, water is produced through basal melting in the catchment region upstream of the lake (as above) with the estimated surface area of 60000 km^2 and an annual water volume available of 0.06 km^3. This melted water should induce an outburst event somewhere in the catchment approximately every 27 yr. Because the overall water flux is conserved, it would, again, take 44 Myr to fill out the observed volume of unconsolidated sediments assuming a sediment concentration in the water of 0.001 by volume (estimated sedimentation rate is $9400 \cdot 10^{-6}$ cm/yr for each outburst event). However, as these outbursts occurred, an increase in the ice elevation over one year of approximately 11 cm over the entire lake area should be observed. Such a significant change in ice surface altitude every few decades would probably not be missed since regular metrological and geophysical observations have been conducted at Vostok Station since the station opening in 1957.

Assuming that 300 m of sediments existed at the bottom of the lake before glaciation (as mentioned previously), and that only 300 km^3 (equivalent to 100 m thick layer of sediments) in the northern basin are deposited through subglacial outbursts it would take approximately 5 Myr to deposit a 100 m thick layer of unconsolidated sediments at the bottom of the lake.

All of the sedimentation mechanisms considered above suggest that Lake Vostok should have existed before glaciation, so some of the sediments were deposited before the ice sheet covered the lake. These may be the sediments that were deposited in pre-glacial Lake Vostok that remained unfrozen during the current glacial event (Duxbury et al., 2001). It is also possible that some of the observed sediments represent the ancient lake floor deposits that were collected before glaciation and then scoured and partially removed by the overriding ice sheet at the onset of the glacial period as suggested by Siegert (2005). Both of those hypotheses imply that there should be a stratighraphy observed in the sedimentary column at the bottom of the lake due to different sedimentation conditions for the bottom and top layers.

Four seismograms recorded in four different locations over the lake were analyzed in a previous research piece (Chapter 5). The seismic records show several closely spaced events after the ice-water echo. These are referred to as secondary bottom reflections. The travel time inversions revealed that some, but not all, of these events are consistent with the hypothesis about the bottom of the lake not being flat with the slopes up to 5 degrees.

In all four locations the top and the bottom of the sedimentary layer were identified. Out of four seismograms analyzed throughout the lake (Chapter 5), the stratighraphy in the sedimentary column was observed in only one location (point 3DL in Figure 5.1). In that location, the sedimentary layer is composed of two parts, each is about 100 m thick with different seismic velocities.

Note, that not all secondary bottom reflections were used for the travel time inversion; only the most pronounced ones were used. It is possible that the less strong events in the recorded seismograms between the top and the bottom of sedimentary layer represent the internal stratigraphy of the sedimentary layer due to different sedimentation conditions. Alternatively, the lack of strong stratigraphy may imply very high sedimentation rates associated with rapid erosion by adjacent valley glaciers at the onset of glaciation.

6.5 Summary

A new 3D bathymetry model of subglacial Lake Vostok, East Antarctica was developed. This model is based on inversion of airborne gravity data, constrained by available to date seismic soundings. The major difference between this model and two previous models is that a value of 2550 kg/m^3 for the host rock density was utilized based on the results of prior 2D modeling. This model also incorporates a new interpretation of the seismic data, suggesting that sedimentary layer is 350 -380 m thick in the northern basin of the lake in contrast to previously reported 50 m. This layer is responsible for a gravity anomaly up to 8 mGal, which is significantly higher than the accuracy of the dataset. All of these lead to a better correlation of the presented model with available seismic data (RMS of the differences in water thickness is 125 m). The estimates for the subglacial sedimentation rates for four possible mechanisms suggest that the lake existed before glaciation in order to accumulate a sedimentary layer of the observed thickness.

The results of this part of my research were presented in August 2007 at the X ISAES, Santa Barbara, CA, where they are published as an extended abstract in on-line Proceeding Volume (Filina et al., 2007b) and are submitted to Earth and Planetary Science Letters (Filina et al., 2007c).

The major results of the study

The research presented focuses on two subglacial lakes of East Antarctica - Lake Vostok and Lake Concordia. Internal processes such as melting/freezing at the ice-water boundary are known to operate in both lakes (Siegert et al., 2000 and 2001; Thoma et al., 2007; Tikku et al., 2005). In order to model those internal processes, the boundary conditions are required that include the distribution of water and unconsolidated sediments in both lakes.

The results of my research over subglacial lakes Vostok and Concordia are the following:

(1) Lake Vostok is hosted by consolidated sedimentary rocks of density 2550 kg/m^3 (Filina et al., 2004, 2006a and 2007b). This conclusion is proven by analysis of the inclusions recovered from the ice core at Vostok Station (Leitchenkov et al., 2007), showing that those inclusions are pieces of sedimentary rock (claystone). This is also consistent with regional modeling of gravity data (Studinger et al., 2003b; Leitchenkov et al., 2003 and 2005), suggesting the presence of a sedimentary basin beneath Lake Vostok.

(2) Lake Vostok consists of two sub-basins: the larger, deeper one in the southern part of the lake with the deepest part more than 1000 m and the shallower one in the northern part, which is several hundred meters deep. These basins are separated by a ~ 40 km wide rise in the lake's bottom. Since the spacing between seismic soundings in this portion of the lake is 40 km, this feature was missed in seismic soundings. This conclusion is consistent with the other 3D bathymetry models (Roy et al., 2005; Studinger et al., 2004), although the presented model (Filina et al., 2007b) has better correlation with seismic data available to date.

(3) Lake Concordia appears to be shallow, as the water thickness can not exceed 200 m for any possible density value of the host rocks (Filina et al., 2004 and 2006a). If Lake Concordia were underlined with igneous rocks of density 3000 kg/m^3 or higher, the lake would not exist, because the water thickness in the lake would be negative. Since the lake is relatively shallow, the sediment layer cannot be resolved. A similar pattern of freezing and melting was observed in Lake Concordia and Lake Vostok: the deeper part of the lake is dominated by freezing of lake's water at the ice-water interface, while in the shallower part the overlying ice sheet melts.

(4) There is a layer of unconsolidated sediments at the bottom of Lake Vostok. The presence of this layer was verified by the analysis of seismic data (Filina et al., 2007a) and later confirmed by modeling of the airborne gravity data (Filina et al., 2007b). This layer is up to 300 m thick in the southern part of the lake and up to 400 m thick in the northern basin. The seismic traveltimes inversion suggests that the velocity of seismic waves in this layer is 1700 – 1900 m/s. The inversion of gravity data shows good correlation with seismic results for the density of sediments of 1850 kg/m^3. Both of these parameters are consistent with unconsolidated, water-saturated sediments.

(5) Estimates for the sedimentation rates under glacial conditions were made based on the observed number of visible inclusions recovered from the ice core at Vostok station. An important assumption was made that the ice velocity, currently observed at Vostok Station, remained constant over the entire glaciation period and was consistent for the entire lake area. The melting rate was also assumed to be invariable since the beginning of glacial period and constant over the entire northern basin. The estimates for four possible sedimentation mechanisms show that none would fill the lake with the observed volume of sediments under glacial conditions, which led to the conclusion that Lake Vostok is of a pre-glacial origin. If we assume the sedimentation rate currently

observed for surface lakes, such as Lake Baikal or Lake Michigan is valid for pre-glacial Lake Vostok, the lake would have to exist at least 500 ky before the onset of glaciation. However, it would take only 2 ky to fill the lake with up to 400 m of unconsolidated sediments if fast periglacial sedimentation based on the rate currently observed in southeastern Alaska is assumed.

Appendix 1: Calculation of the gravity anomaly due to a 2D body with polygonal cross-section

To solve the forward problem in the case of 2D modeling Talwani's method for calculation of a gravity anomaly due to a 2D body with a polygonal cross section (Grant and West, 1965) was used. The major idea of the method is to represent the cross-section of an anomalous body with an N-sided polygon. A spatial coordinate (*x*) and depth (*z*) should be assigned to each of the polygon's vertices (see Figure A1.1). For the correct calculation the polygon should be closed, i.e the N+1 points should be used with (x_{N+1}, z_{N+1}) $\equiv$ (x_1, z_1).

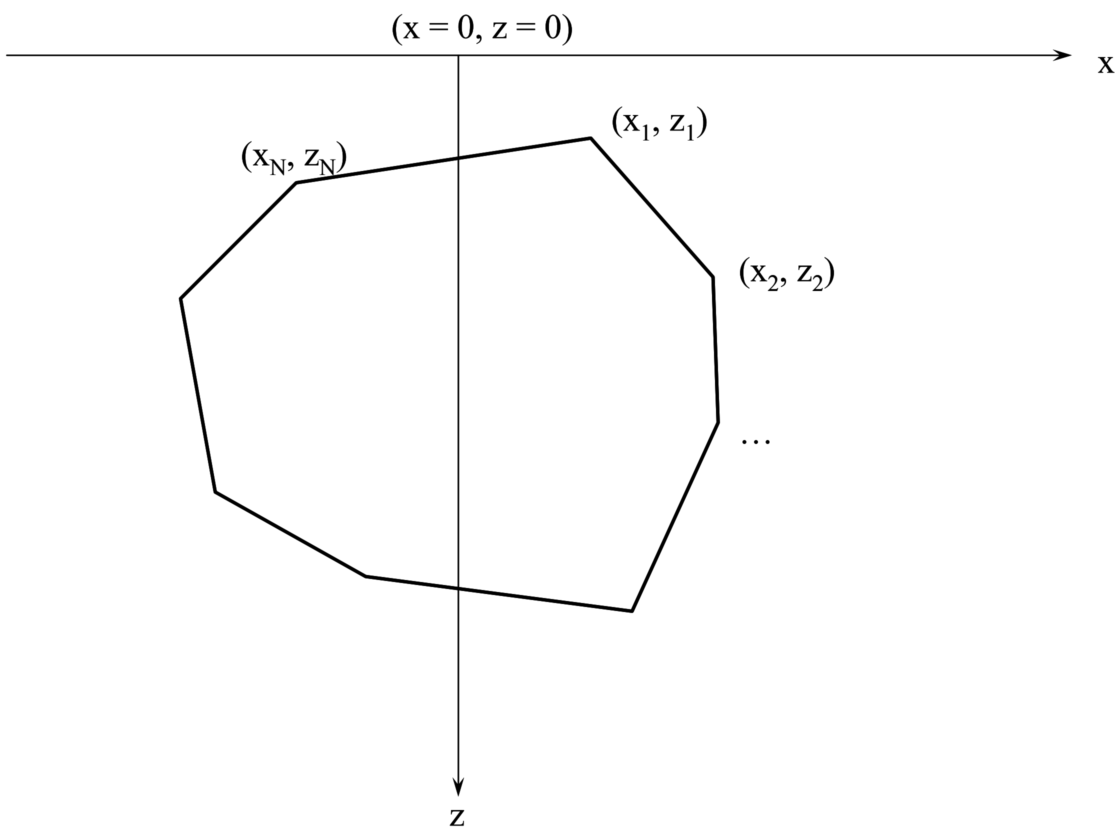


Figure A1.1 The cross section of the 2D body represented as an N-sided polygon

The gravity effect at the zero level due to the 2D polygonal body is given by the following equation:

$$g = 2G\Delta\rho\sum_{k=1}^{N}\frac{b_k}{1+a_k^2}\left[\frac{1}{2}\ln\left(\frac{x_{k+1}^2+z_{k+1}^2}{x_k^2+z_k^2}\right)+a_k\left(\tan^{-1}\frac{x_{k+1}}{z_{k+1}}-\tan^{-1}\frac{x_k}{z_k}\right)\right]$$
$$a_k = \frac{x_{k+1}-x_k}{z_{k+1}-z_k}, b_k = \frac{x_k z_{k+1}-x_{k+1}z_k}{z_{k+1}-z_k} \qquad \text{(A1.1)}$$

where G –gravitational constant,

Δρ is density contrast with surrounding rocks,

x_k and z_k are coordinates of N body's corners.

To avoid zeros in denominator some simple mathematical transformation of the initial formula was done:

$$g = 2G\Delta\rho\sum_{k=1}^{N}\frac{(x_k z_{k+1}-x_{k+1}z_k)}{(\Delta x_k^{\ 2}+\Delta z_k^{\ 2})}\left[\frac{1}{2}\Delta z_k\ln\left(\frac{x_{k+1}^2+z_{k+1}^2}{x_k^2+z_k^2}\right)+\Delta x_k\left(\tan^{-1}\frac{x_{k+1}}{z_{k+1}}-\tan^{-1}\frac{x_k}{z_k}\right)\right]$$
$$\Delta x_k = x_{k+1}-x_k, \qquad \text{(A.1.2)}$$
$$\Delta z_k = z_{k+1}-z_k$$

The above equation allows relatively fast calculation of the gravity anomaly at the z = 0 observation level. If the observed gravity anomaly was measured at the different level, it should be either upward or downward continued to the zero level, or the appropriate shift in all z-coordinates for the polygon should be made before calculating the gravity anomaly due to this anomalous body.

Appendix 2: Calculation of the gravity anomaly due to a 3D prism

In the case of 3D modeling, the anomalous layers are composed of a number of rectangular prisms of various sizes. (Figure A2.1). The gravity effect of every prism was then calculated assuming the density contrast between those layers and the host rocks was constant for each prism, based on the equation of Nagy (2000):

$$g = G\Delta\rho \left|\left|\left| x\ln(y+r) + y\ln(x+r) - z\tan^{-1}\frac{xy}{zr} \right|_{x_1}^{x_2}\right|_{y_1}^{y_2}\right|_{z_1}^{z_2} \quad \text{(A2.1)}$$

where x, y, and z are the prisms coordinates with respect to the point where the gravity effect g is being calculated (see Figure A2.1);

$r(x,y,z) = \sqrt{x^2 + y^2 + z^2}$

G – gravitational constant,

$\Delta\rho$ is density contrast with the surrounding rocks.

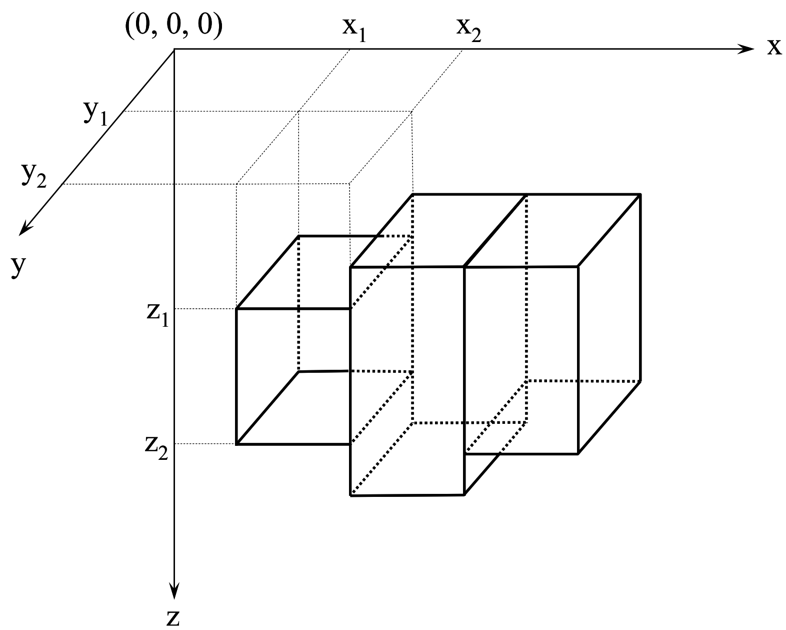


Figure A2.1 The anomalous layer in 3D represented as a set of prisms. The gravity effect is calculated in the point $O(0,0,0)$.

Appendix 3: The algorithm used to reduce airborne gravity data

The algorithm for airborne gravity data reduction was developed by Thomas Richter of UTIG (Richter et al, 2001, 2002; Holt et al., 2006) by the general method which has become standard in the industry - GPS positions are used to calculate nongravitational accelerations on the gravimeter, which are subtracted from the total vertical acceleration recorded by the gravimeter. The gravity corrections were calculated from GPS positioning data (latitude, longitude, aircraft height with respect to sea level) and the surface elevation from laser altimeter. All these data were acquired along the same profiles coincident with gravity with one-second sampling interval. An example of the data recorded by a gravity meter is shown in Figure A3.1. a.

The algorithm includes three main steps:

Step I: Calculation of the total gravity correction from GPS data.

The total correction is shown in Figure A3.1.b. This correction was calculated as a sum of the following components:

1. Aircraft vertical acceleration; it was calculated by applying the second derivative filter to the aircraft height.
2. Free-air correction; this correction is linearly proportional to the aircraft height with the coefficient of 0.3086.
3. Eotvos correction; this was calculated based on algorithm of R.B. Harlan (1968).
4. Theoretical gravity; it was calculated based on the following equation (GRS80):

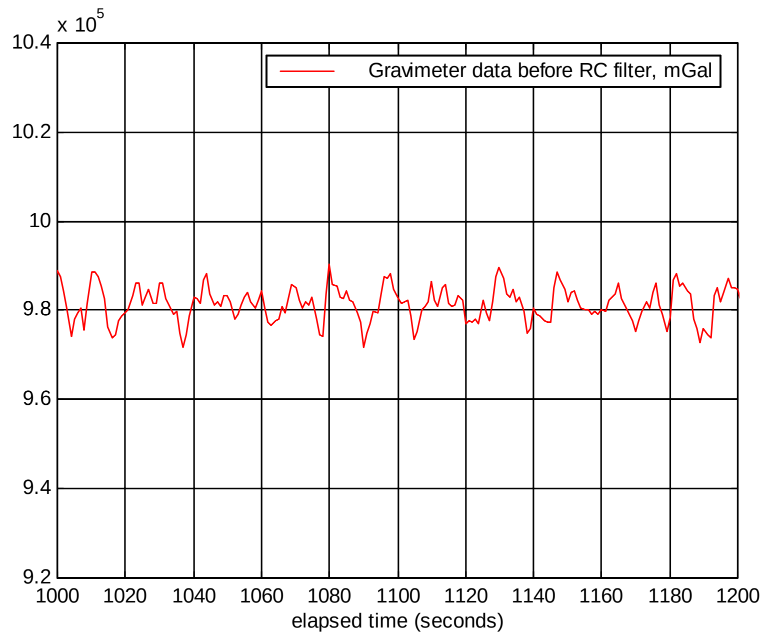
$$g_t = g_0 * (1 + k_1 * \sin^2 \varphi + k_2 \sin^4 \varphi)$$

where g_t is theoretical gravity value,

φ is the latitude, $g_0 = 978032.67715$,

$k_1 = 0.0052790414$, $k_2 = 0.0000232718$

a.



b.

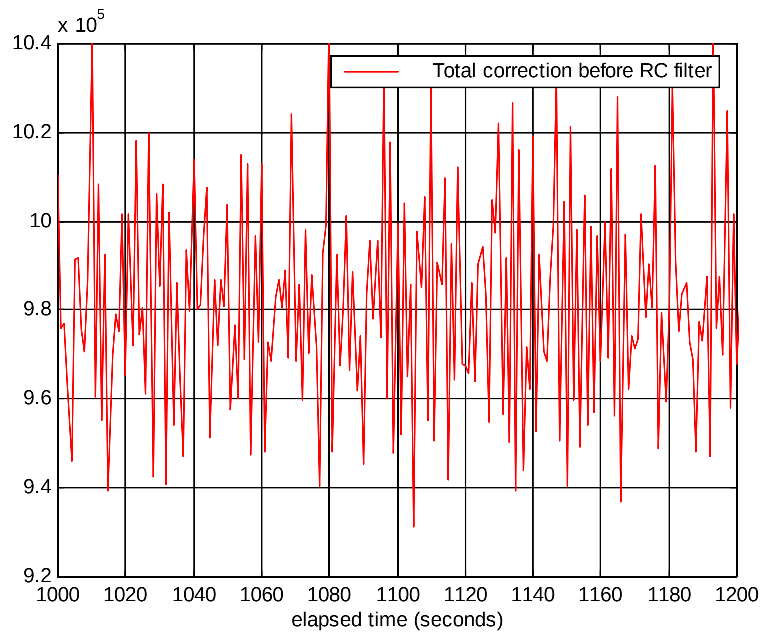


Figure A3.1 Illustration of the Step I of the reduction algorithm
a. Gravimeter data in mGal from WLK survey (1999 -2000 season);
b. Total correction in mGal.

Step II: RC filtering.

An RC filter was used as a digital simulation of the resistor – capacitor network in the gravimeter electronics, which was applied to the gravity data before recording. The time constant for the RC filter was 4.5 sec (from gravimeter manual). The transfer function of this filter is shown in Figure A3.2.a.

Such filtering results in phase distortion and delays. To remove this effect, reverse RC filtering of the gravimeter data was applied (Figure A3.2.b). To create the same effect the forward and reverse filtering of total correction was applied (Figure A3.2.c).

a.

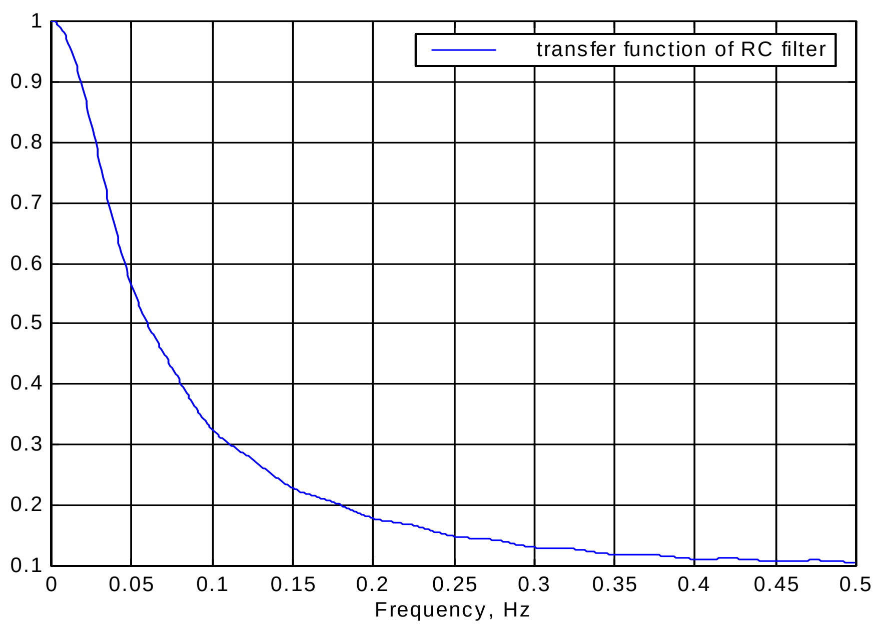
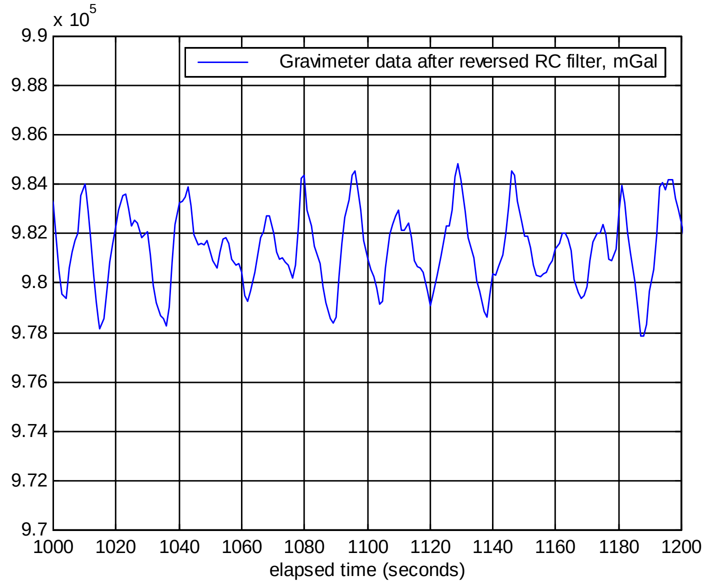


Figure A3.2 Illustration of the Step II of the reduction algorithm

a. Transfer function of RC filter

b.



c.

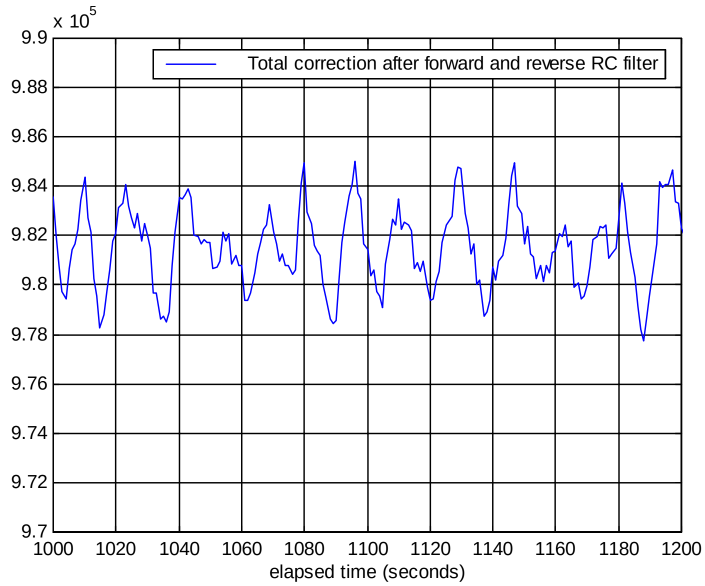


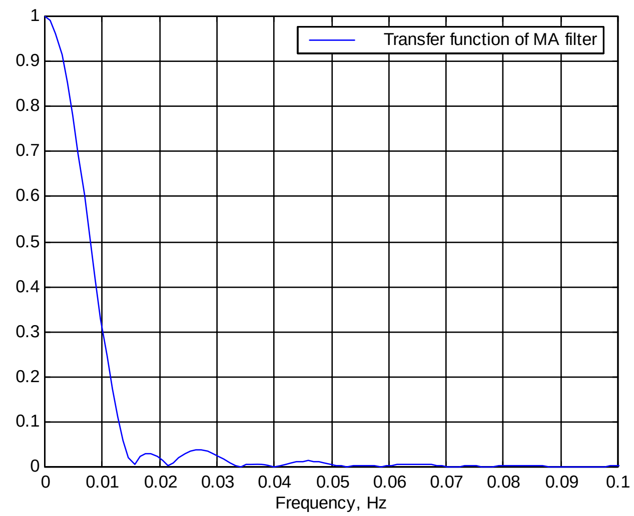
Figure A3.2 (Continued)

b. Gravimeter data after reverse RC filter;

c. Total correction after forward and reverse RC filter.

Step III. To obtain the free-air anomaly, the total correction is subtracted from the recorded gravity data. The difference still contains significant noise, thus final filtering of this difference is performed with a spatial Moving Average (MA) filter 15 km wide (Figure A3.3). The filter coefficients are calculated using the triweight function $b = 35/32(1\text{-}d^2)^3$.

a.



b.

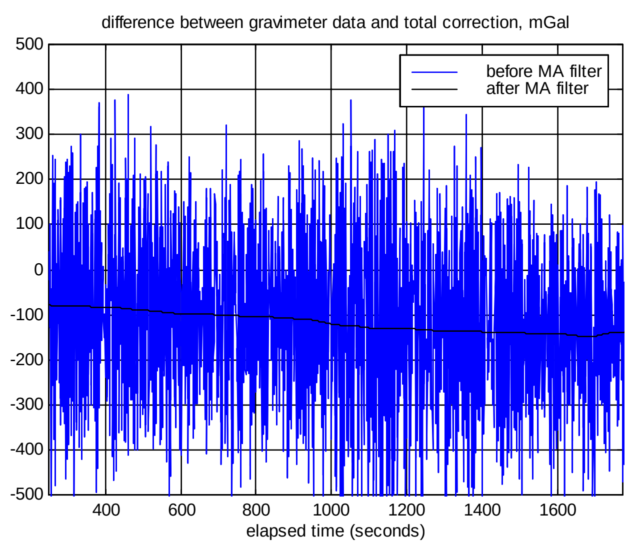


Figure A3.3 Illustrations of the Step III of the reduction algorithm
a. Transfer function of the MA filter;
b. The free-air anomaly before and after the MA filter.

The data for a repeated line were used to estimate the accuracy of the free-air anomaly. This line was re-flown due to bad weather conditions, so it represents one of the worse gravity profiles. The reduced data for two profiles flown along the same line are shown in Figure A3.4. Each of those lines has 1450 overlapping data points. The mean value of the difference is 3.75 mGal, while the RMS of the difference is 1.6 mGal.

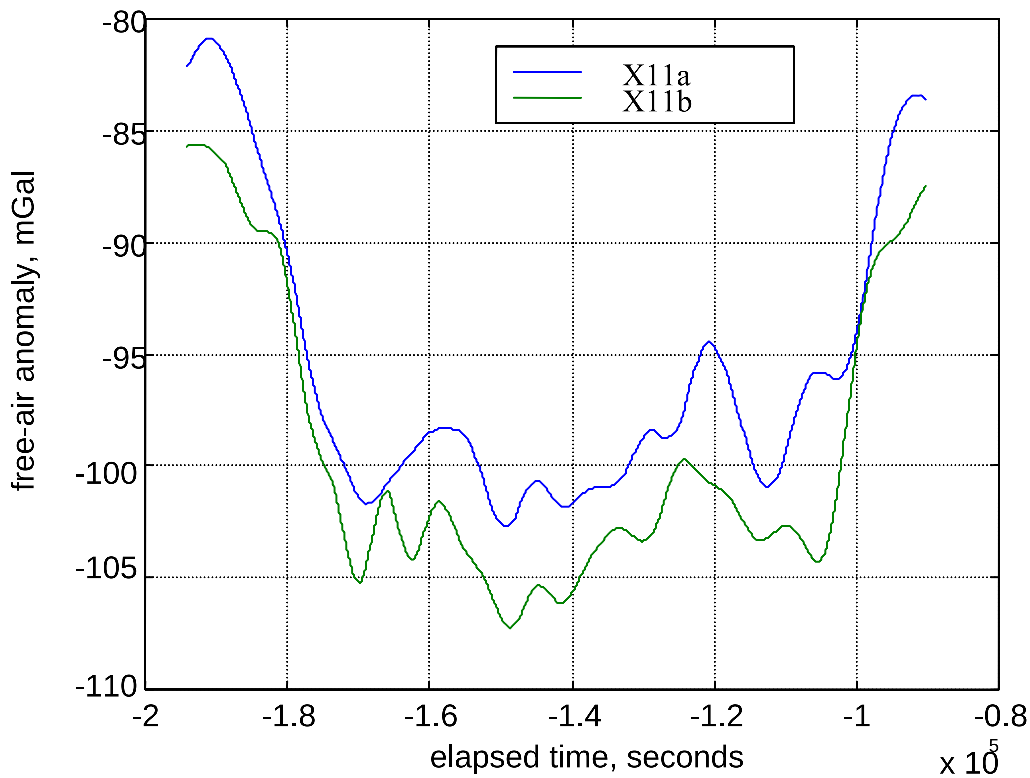


Figure A3.4 Free-air anomaly for two profiles along the same line

Appendix 4: The concentration of sediments in the ice estimated from 5G-1 borehole data

The core samples from the 5G-1 borehole suggest that below the depth of 3538 m the ice was formed by freezing from the Vostok lake water (Jouzel et al., 1999; Chapter 2). The top 70 m of the accreted ice is referred to as "muddy ice" due to inclusions observed in this layer. Some of those inclusions are visible with the dimensions up to 4.5 mm (Leitchenkov et al., 2007; Chapter 2; Figure 2.2). The total number of visible inclusions increases dramatically in the top section of the "muddy ice", counting up to 30 inclusions per one meter of the core (Figure 2.2.c). The smaller inclusions with the average dimension of 6.7 μm are also observed in the muddy ice (Royston-Bishop, 2005).

Based on the parameters known from the core, the total amount of sediments in the accreted ice may be estimated. This should be done separately for both large visible inclusions and small ones.

Estimate for the small inclusions (average dimension of 6.7 μm) is based on the paper of Royston-Bishop at al. (2005). The results of this paper are based on the four samples from different parts of the muddy ice with the total mass of 70 g. This mass of the samples is equivalent of 76 cm^3 of ice (density of 0.92 g/cm^3). Royston-Bishop at al. (2005) observed 727 inclusions in those four samples. If we assume that each aggregate particle is a sphere with the diameter of 6.7 μm, than the total volume of observed aggregates in 76 cm^3 of ice is:

$$\frac{4}{3}\pi(\frac{1}{2}6.7*10^{-6}m)^3*727 = 1.2*10^{-13}m^3 = 12*10^{-8}cm^3$$

This gives the average concentration of the small inclusions (average dimension of 6.7 μm) the muddy ice of $0.16*10^{-8}$.

Two different estimates may be done for the visible inclusions. The maximal number observed is 30 per one meter of the ice core. If we assume that each of those may be approximated with a sphere of 2 mm diameter, the maximal concentration of visible inclusions in ice (one meter-long ice sample with diameter of 10 cm= 0.1 m) is:

$$\frac{\frac{4}{3}\pi(1*10^{-3}m)^3*30}{\pi(0.05m)^2*1m}=16*10^{-6}$$

The total number of visible inclusions is estimated to be 465 in the 70 m-thick "muddy ice" (Figure 2.2.c). The average concentration may be estimated assuming in the ice sample:

$$\frac{\frac{4}{3}\pi(1*10^{-3}m)^3*465}{\pi(0.05m)^2*70m}=3.6*10^{-6}$$

The volume of visible inclusions is at least two orders larger than the one of the small inclusions, so the last one may be disregarded for the estimates of sedimentation rates.

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Vita

Irina Filina was born in Leningrad, USSR on September 20, 1974, the daughter of Galina Filina and Yuriy Filin. After graduating from the High School No. 32 of Saint Petersburg, Russia in 1991, she entered the Department of Physics of Saint Petersburg State University (SPSU). She received her Bachelor of Science degree in Physics in May 1995 and her Master of Science degree (also in Physics) in 1998 with specialization in nuclear magnetic resonance. While working on her Masters Degree during 1995 -1998 she was employed as a teacher of Mathematics at the Middle School No. 21 of Saint Petersburg, Russia.

After graduation from SPSU Irina worked as an engineer in Polar Marine Geological Research Expedition (PMGRE), Saint Petersburg, Russia. Her primary responsibilities were to process radar sounding data for multiple surveys. During three years of her work in PMGRE she participated in three Arctic field seasons (1998, 1999 and 2000). All three were airborne geophysical surveys of the Franz Josef Land Archipelago. She also went to one field trip to the Vostok Station, East Antarctica.

Irina joined the University of Texas at Austin in 2002 to pursue the PhD in Geological Sciences. Since then she has been working under the supervision of Dr. Donald D. Blankenship in the University of Texas Institute for Geophysics (UTIG). The major object of her research is the subglacial Lake Vostok in East Antarctica. Irina is currently involved in the collaborative project between UTIG, PMGRE and the Russian Antarctic Expedition. The ultimate goal of this project and the Discussion of this Dissertation is to interpret jointly different geophysical datasets to reveal the geological information about this lake, such as verify the presence of unconsolidated sediments at the bottom of the lake, develop 3D models of water and sediment distribution, as well as establish what type of rocks host the lake. Irina's publications about subglacial lakes of Antarctica are listed in the Bibliography section of this Dissertation.

Irina's teaching experience at the college level includes three semesters of being Teaching Assistant at the Department of Geological Sciences of the University of Texas at Austin during 2005 -2007 and being an Adjunct Faculty in the Austin Community College in 2007.

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